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THE ENGLISH ELECTRIC JOURNAL

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Editorial

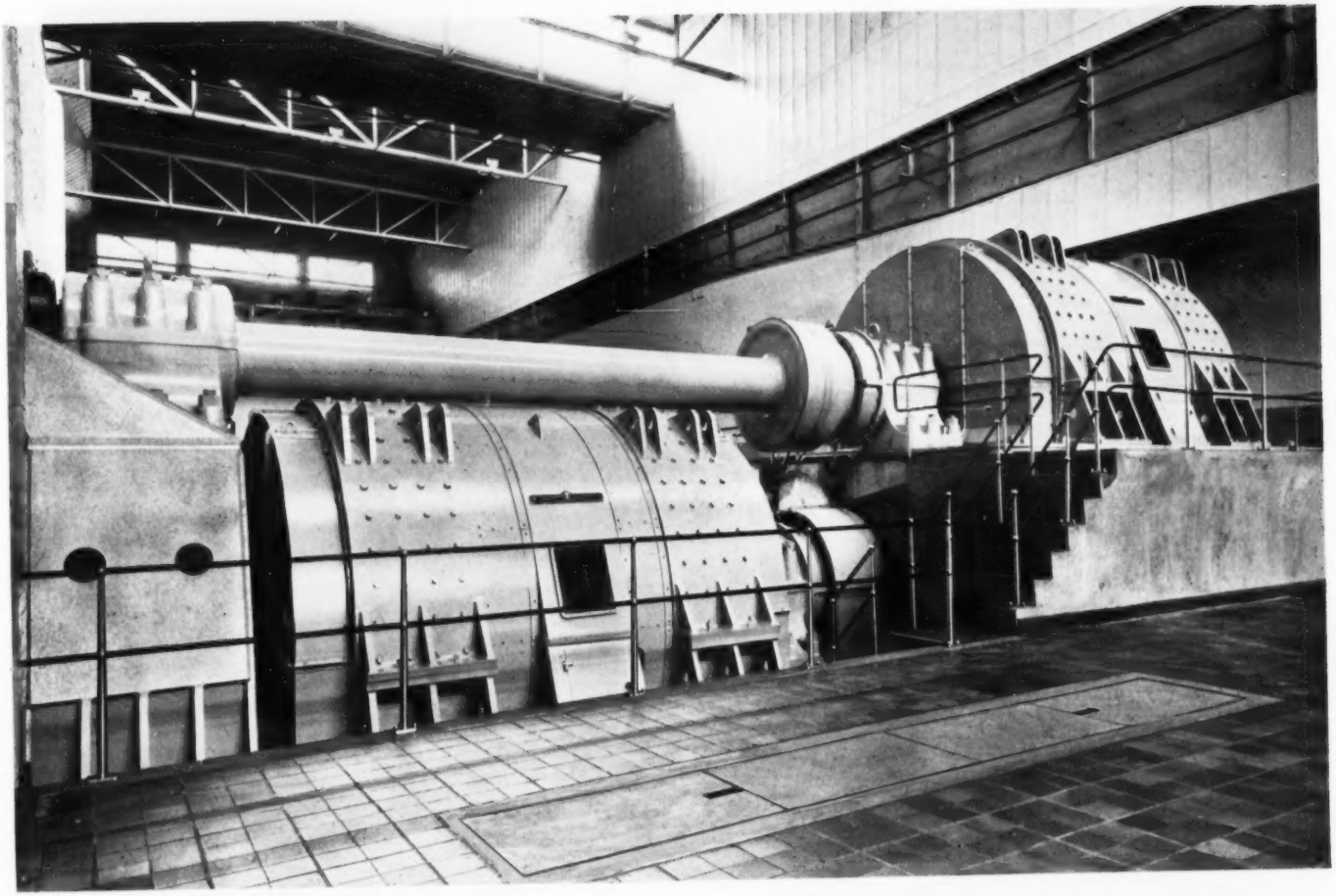
In this issue a series of articles commences describing 'English Electric' equipment installed in the Abbey Works of the Steel Company of Wales.

The need for a large increase in the capacity of the British steel industry to produce cold-rolled steel strip became apparent towards the end of the 1939-1945 war. The creation of a new steel plant to produce about 2 million tons a year, and to roll this quantity down to slabs and then to strips, especially with a large proportion of the strip in the range of tinplate gauges, was a considerable problem, and the size of the project to give the lowest production costs was such that the necessary resources could best be provided by several companies acting together. Accordingly, the Steel Company of Wales was formed by the combination of a number of large British steel firms.

The possible sites were limited, and the final scheme resulted in the steel-making, hot rolling, and heavier cold rolling being located in the new Abbey Works at Port Talbot, and the thinner cold rolling and tinplate activities at a separate works at Trostre near Llanelly, a few miles away.

Electrical equipment plays a most important part in such processes, and The English Electric Company contributed rolling mill drives, switchgear, transformers, industrial motors and fusegear. This Company also supplied the switchgear and transformers for the South Wales Electricity Board's 66/11 kV substation, exclusively for feeding the Abbey Works.

All communications respecting Editorial Contents should be addressed to The Editor, THE ENGLISH ELECTRIC JOURNAL, THE ENGLISH ELECTRIC COMPANY, LIMITED, STAFFORD, ENGLAND.



The twin motor drive for the 45 inch slabbing mill at the Abbey Works of the Steel Company of Wales Limited

'English Electric' Equipment at the Abbey Works of the Steel Company of Wales

I. TWIN MOTOR DRIVE FOR 45 INCH SLABBING MILL

By H. S. BROWN, B.Eng., A.M.I.E.E., Metal Industries Division

THE FIRST OF the many mills to roll the steel at the Abbey Works is the slabbing mill. This large reversing mill provides the material for the rest of the mills to work upon, receiving ingots weighing up to 20 tons and rolling them to slabs of varying thickness and width, the minimum thickness being about 5″ and the maximum width about 60″.

Although mills of this size are now being built in Great Britain, this was not possible immediately after the last war, and the slabbing mill for the Abbey Works was therefore obtained from America and was manufactured by the United Engineering & Foundry Company.

Messrs. McLellan & Partners were the consultants for the whole of the electrical equipment installed at the Abbey Works.

Molten Steel to Cold Strip

Before describing the mill and its drive a brief survey of how the steel reaches the mill and of the subsequent work on the slabs which it rolls may be of interest to those not familiar with steel works.

Steel to feed the slabbing mill comes from 60/80 ton open hearth furnaces at the Margam and Port Talbot Works and from the new melting shop at the Abbey Works, which is equipped with eight 200-ton furnaces. These furnaces use approximately 50% pig iron and 50% scrap steel and can produce about 20,000 tons of steel per week.

The charge from the furnaces is poured into ladles of 200 tons capacity carried by 300-ton overhead cranes. From the ladles the steel is poured into moulds which cast it into ingots ranging in size from 7½ tons measuring 36″ × 27¼″ × 70″ to 20 tons measuring 66″ × 32¾″ × 82½″.

As soon as the outer part of each ingot is solid, the mould is stripped off and the ingot transferred to the soaking pits where it is left until it is at a uniform temperature throughout. The soaking pits, which are gas fired, lie at the entry end of the mill bay and comprise 20 pits each 15′ × 16′ × 11′.

When ready, each ingot is lifted out of the soaking pits by one of two 20-ton overhead charging cranes and deposited on the ingot car. This car runs the whole length of the pits, in line with the mill tables, and carries the ingots on to the roller tables feeding the slabbing mill.

As many as 35 passes may be taken in the slabbing mill to reduce the ingot to the required slab, depending upon the size of ingot and slab.

After the last pass, the slabs are delivered by roller tables to the slab shear where they are cropped and cut into lengths. The cut slabs are fed to a slab yard where they are allowed to cool before being inspected and dressed.

From the stock in the slab yard, slabs are fed through any one of three re-heating furnaces to the 11-stand 80-inch continuous hot strip mill. Depending on their thickness, which may vary between 0.75″ and 0.05″, the products of this mill are either coiled or sheared into lengths. The coils which may weigh up to nearly 20 tons are carried on a conveyor to the pickling line and cold mills. The cut lengths may be carried straight through on roller tables to the plate finishing departments, or may be piled for transfer to the sheet finishing department.

The Slabbing Mill

This mill, which is the largest of its type installed in Great Britain and amongst the largest in the

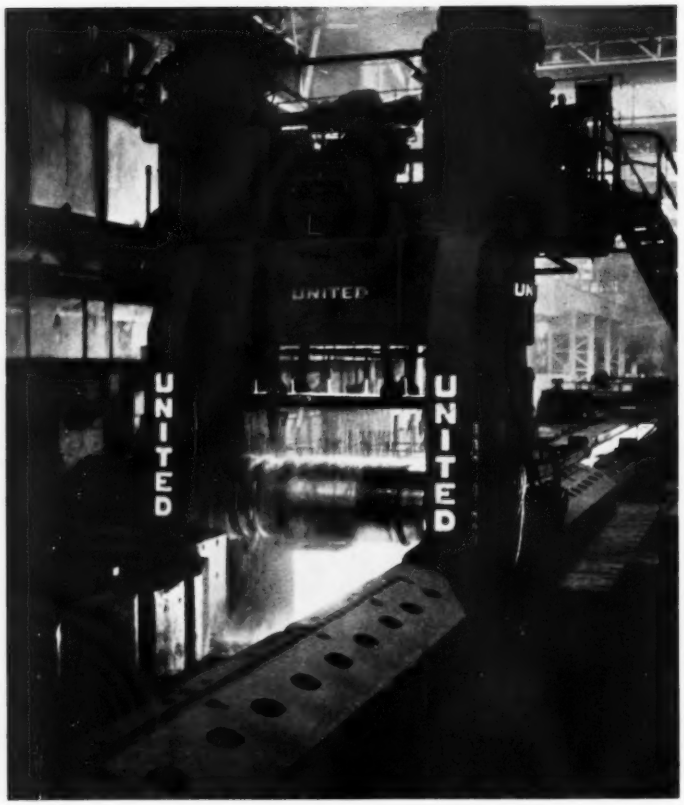


Fig. 1. *The slabbing mill from the entry side*

world, lies 113 feet from the first roller of the receiving table. Fig. 1 shows the mill with a new ingot being rolled and a finished slab travelling down to the shear.

The mill has two rolls each 45″ maximum diameter with a barrel length of 115″, which run in taper roller bearings ; it is one of the very few mills of this type on which roller bearings have been fitted. Ingots weighing up to 20 tons and up to 66″ wide can be handled, the maximum opening of the rolls being 68″. The size of the mill will be appreciated from the fact that the two main housings each weigh 125 tons and are over 30 feet high. The screws for adjusting the position of the top roll are 18″ diameter and give a maximum speed of roll adjustment of just over 500 inches per minute. The top roll is counter-balanced by dead weights so that it is always held up against the bases of the screws.

Main Mill Drive

One of the distinctive features of the slabbing mill is the size of the drive and the fact that a separate motor is used to drive each roll. A résumé of previous practice and of the basic requirements of reversing mill drives will enable this and other features of the drive to be more readily appreciated.

Two basic requirements must obviously be met by a reversing mill drive. It must be able to accelerate and decelerate rapidly, and it must have a high torque output to enable reasonably large reductions to be taken on the large ingots.

The first of these requirements means that the inertia of the drive referred to the mill rolls must be kept at a minimum. The second, in conjunction with the speed, determines the power of the drive. In slabbing mills, high speeds are not required since the slabs are never much more than 50 feet long.

The majority of reversing mills at present installed have their rolls driven by a single driving unit. This is either an electric motor, or in the older mills a steam engine, driving a pair of pinions which transmit the drive to both top and bottom rolls. Although the lesser inertia of the steam engine gives it a distinct advantage, this is far outweighed by the greater economy in running and maintenance costs shown by the electric drive, and also by the fact that the latter is easier to control and makes a much neater and cleaner installation. During the last 20 years or more almost all reversing mill drives installed have been electric, and many steam drives have been replaced by electric drives.

Many years ago it was realised that instead of using a single driving motor and pinions, two

motors could be used, one driving each roll direct. This arrangement offers a number of advantages amongst which are :—

Elimination of pinion housing, with the associated pinion losses, giving a saving in energy consumption of 4 to 5%.

Omission of pinion lubrication system.

Replacement costs of pinion avoided.

The speeds of the rolls are not tied rigidly together.

The inertia of a twin motor drive is less than that of the equivalent single motor drive.

With a twin drive, slip between the rolls and metal due to any difference in roll diameter is avoided, with consequent reduction in roll wear.

Doubts were raised, however, as to whether it would be possible to roll successfully with a separate motor on each roll. Some operators feared that due to possible inaccuracies in the control of the motors difficulty might be experienced in entering the piece, or that once it was entered it might tend to curl up or down due to unequal torques on the rolls.

To prove whether or not these doubts were justified, tests were carried out by The English Electric Company in 1922 on a three-stand mill rolling 19″ square ingots to 18″×¾″ flats. These tests proved that very satisfactory rolling could be obtained with separately driven rolls, even though the two motors used were by no means identical, and there was ½″ difference in diameter between the upper and lower finishing stand rolls.

Despite the results of these tests the twin drive was not adopted in Great Britain until 1934 when The English Electric Company installed a small twin drive for a universal 24″ non-ferrous reversing mill at the Witton Works of Imperial Chemical Industries Limited. This drive was unique also in that the twin motors (connected in series) for the horizontal rolls, and also the motor driving the vertical rolls, were all supplied from one generator. Fig. 2 shows the three driving motors ; the two driving the horizontal rolls have a combined cut-out torque of 355,000 lb ft.

When the drive for the new Abbey Works slabbing mill was being considered, a twin drive was decided upon at the outset. Rolling programmes were calculated and these showed that a drive with a cut-out torque of 3,600,000 lb ft would do the duty, and that speeds of 0/40 r.p.m. at constant torque and 40/80 r.p.m. at constant horse-power would be suitable.

In accordance with normal British practice the R.M.S. rating was based on a 40°C. temperature rise with a ratio of cut-out torque to R.M.S. torque of 3 : 1. This gave an R.M.S. rating of 9,200 h.p. at 40/80 r.p.m. The corresponding American rating of 10,000 h.p. normally specified for these drives is based on a 50°C. rise and a ratio

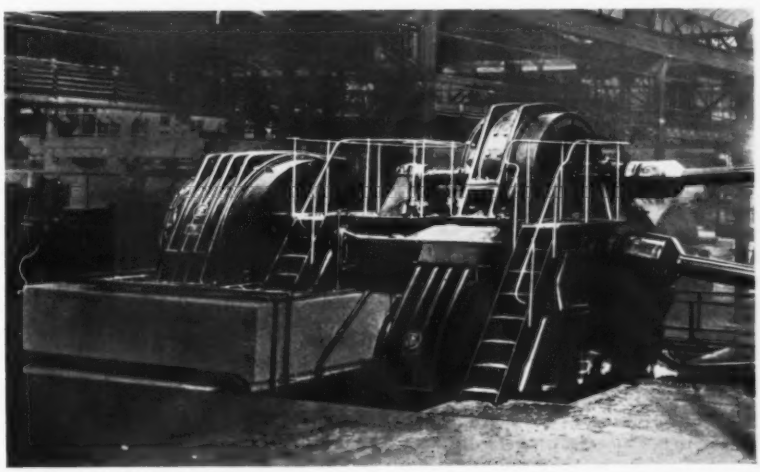


Fig. 2. The first twin drive installed in Great Britain, for a 24 inch non-ferrous reversing mill at the Witton Works of Imperial Chemical Industries Limited. The motor driving the vertical rolls is mounted above the lower main motor

of cut-out torque to R.M.S. torque of 2.75 : 1, giving a similar cut-out of 3,600,000 lb ft.

The rating having been fixed, consideration was given to whether the motors should be of the single armature or double armature type. Linked with this problem was the allowable height between centres of the two motors. This in turn was affected by the maximum angle at which it was considered satisfactory to work the universal spindles connecting the motors to the mill, and also by the length of these spindles. The first American twin drives had been installed with a height between motor centres of 83½ inches and a spindle length of 25 ft. With 54″ diameter rolls, this gave spindle angles of 2.5° and 3° upwards for new and old bottom rolls respectively, whilst the upper roll spindle angles were 4.9° upwards

Fig. 3. North end of slabbing mill motor room, showing layout of main drive equipment

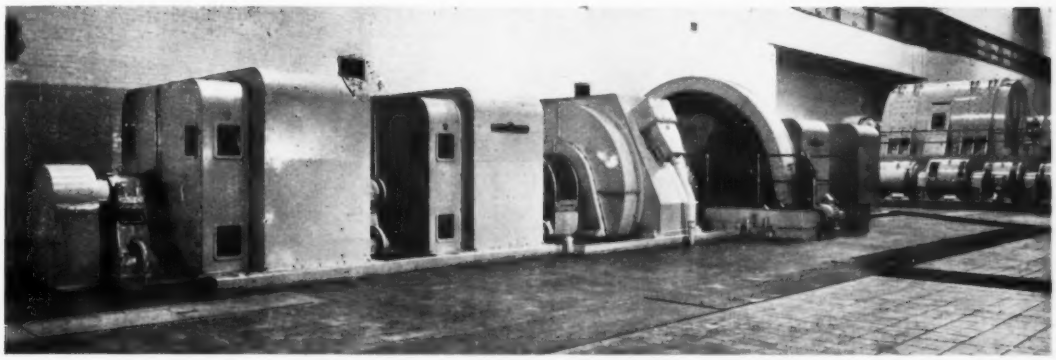


Fig. 4. *The Ilgner set*

in the highest position with a new roll, and 3.7° downwards in the lowest position with an old roll.

Experience showed that these angles gave completely satisfactory operation. Similar angles were therefore adopted in later twin drives in America but longer spindles were used to allow a greater height between motor centres. In particular, spindle lengths of about 31 ft were adopted for 45″ slabbing mills, which permitted 94″ between motor centres. As the Abbey slabbing mill was to be of American manufacture, centres of 94″ were adhered to.

American drives of 10,000 h.p. with 94″ centres all use two single armature motors. After investigating various designs for the Abbey Works drive it was decided that a single armature motor was approaching the limits of satisfactory commutation, and a double armature design was therefore chosen.

The Ilgner set could then be decided upon. As there were four motor armatures, and a series connection was to be used for reasons given later, four generators were chosen. This gave a very satisfactory electrical arrangement and also in an emergency permitted two generators to be disconnected and the mill run on the remaining generators at half speed, but with full torque available.

The rolling programmes showed that a 6,500 h.p. induction motor with a 200,000 h.p. seconds flywheel would be required to drive the Ilgner set. Rather more than 6,500 h.p. would be required to prevent too great a speed drop when rolling the last passes of the heaviest slabs, or when rolling certain slabs in tandem. The control was therefore arranged to allow the Ilgner motor to take up to 20% overload, when the R.M.S. load would still be well within the rating of the motor.

Arrangement of Equipment

The general layout of the equipment is shown in Fig. 3.

In the foreground are the two double-armature main motors, another view of which is given in the frontispiece. These are two-pedestal bearing type machines. The drive from the upper motor is transmitted over the lower motor by a jack-shaft. The outer end of this shaft runs in a journal bearing carried on an ' A ' frame above the driving-end bearing of the lower motor. This ' A ' frame also supports the driven end of the upper mill spindle carrier beams. The more normal arrangement of placing the commutators at the outer ends of the armatures would not have been satisfactory for this drive, as the presence of the ' A ' frame would have made the driving-end commutator of the lower motor inaccessible ; the two commutators on each motor are therefore in the middle of the machine. This arrangement also facilitates the extraction of the commutator air.

Behind the main motors, on the right, are the Ilgner set and liquid slip regulator. All the machines of the Ilgner set (shown also in Fig. 4,) are of the normal single-pedestal bearing type, except that the generators have special commutator enclosures.

On the left in Fig. 3 one end of the main exciter

Fig. 5. Motor room control desk, with alarm and recorder panel on extreme right and contactor board for the main and feed roll drives to the right of the exciter sets

set can be seen with the control exciter set at right angles to it. On the left of the exciter set is the contactor board for the main mill drive and the feed roll drive. Beyond this is the motor room control desk and alarm panel, and one section of the contactor board for the main drive auxiliaries ; the other section is in the basement.

Starting and permissive control is centralised on the motor room control desk shown in Fig. 5. The alarms and recording instruments are mounted on a separate cubicle standing behind the desk.

Control of the main drive is through the foot-operated master controller seen in Fig. 6. As the mill is controlled by two operators only, it is essential that foot-operated controllers be used for some drives, and the main drive was considered to be one of the most suitable. The pulpit instruments are mounted in a vertical cubicle on the right of the pulpit (Fig. 7). They comprise top and bottom roll ammeters and speed indicators, and a mid-wire ammeter. The first four are 12″ edgewise pattern and the last is 4″ square. All are illuminated. The cubicle also carries the rheostats for adjusting the differential speed and torque control. One rheostat graded in torque ratio provides the differential torque control, whilst two rheostats are provided for the differential speed control, one being graduated in terms of top roll diameter and the other in terms of bottom roll diameter.

Main Drive Control

The control of a twin drive for a reversing mill can be considered in two sections. Firstly, the method of controlling the speed and direction of rotation ; this part of the control is the same for both single drives and twin drives. Secondly, any additional features required to control the relationship of load and speed between the two motors.

The speed control of the slabbing mill main drive is effected in two stages ; first armature voltage control at full field, followed by motor field weakening at full armature volts. This method is almost universal for primary reversing mills as it enables the maximum throughput of steel to be obtained for a given motor size. That this is so can be appreciated when the rolling duty for this type of mill is considered. In the early stages the piece is of large cross sectional area and short, so that output is little affected by mill speed and, in fact, there is insufficient time to accelerate to high speeds. In the later stages the cross sectional area is greatly reduced and the length proportionately increased. In the case of blooms both the width and the depth are greatly reduced so that the rolling torque is much less. At the same time, however, the greatly increased length of piece makes higher mill speeds advantageous. Motor field weakening is thus a most suitable way of obtaining this higher speed. Within limits, it enables the motor speed to be increased with a proportionate decrease in torque (i.e. constant

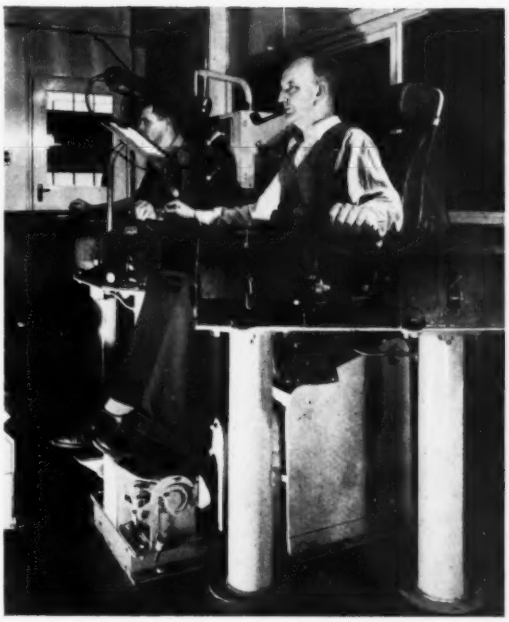


Fig. 6. Interior of main mill pulpit, showing the foot-operated controller for the main drive beneath the chair of the nearer operator

horse-power) without any increase in the size of the motor or the generator feeding it.

With slabbing mills the advantage of field weakening is not so great, as the width of the final slab often does not differ greatly from that of the initial ingot. Although not so often applicable, the higher speeds with weak field can be used when rolling narrow slabs, and a field weakened speed is therefore normally provided.

In the case of the Abbey mill, a speed range of 0/40 r.p.m. by voltage control and 40/80 r.p.m. by field weakening was chosen, as already mentioned.

Armature Circuit Arrangement

The generator and motor armatures are connected in series, in accordance with The English Electric Company's preferred practice. Two advantages of this arrangement are :—

(*a*) The series connection ensures inherent load sharing between generators and motors, without the need for cross compounding.

(*b*) If one or more generators are for any reason taken out of circuit, the mill drive can still provide full torque. The rolling programme

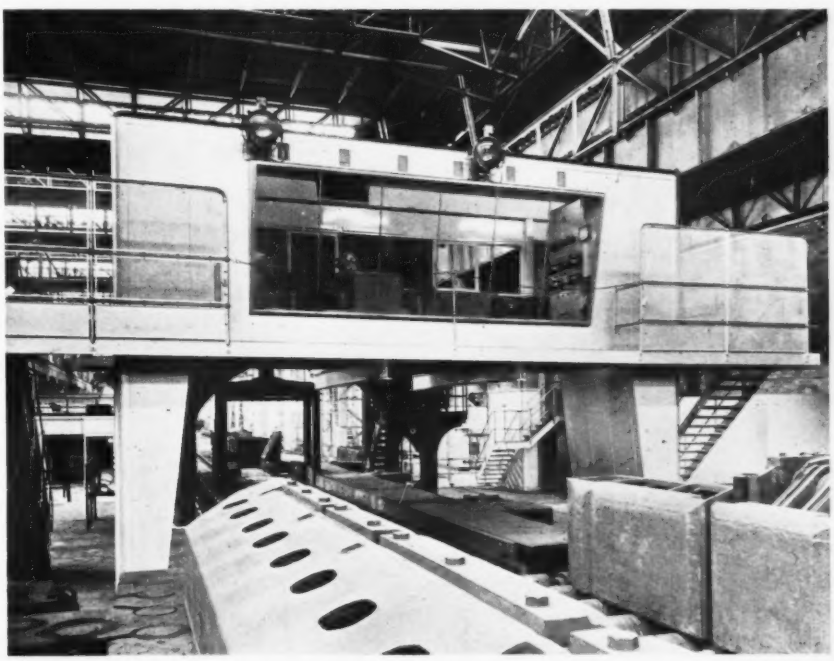


Fig. 7. Main mill pulpit as seen from the mill

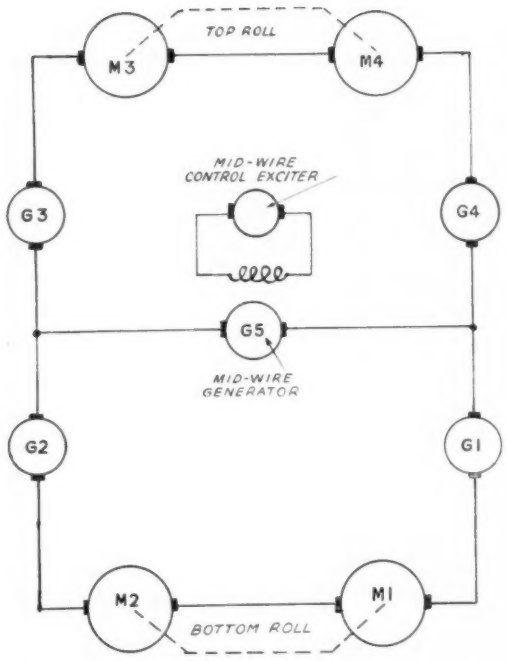


Fig. 8. *Basic connections of main armature circuit*

can thus remain the same although the rolling speed is reduced. With half the generators out of circuit a production of, say, 75 to 80% normal could be obtained. If the generators are in parallel the torque capabilities of the drive are reduced. This necessitates an increase in the number of passes with a corresponding increase in the number of intervals, the effect of which more than outweighs the advantage of being able to roll at full speed. With half the generators out of circuit the output would probably fall to 65 or 70% normal.

Further, the generators and motors are connected in sandwich as shown in Fig. 8. By earthing the circuit between two generators, the maximum operating voltage to earth is limited to that of one generator.

Differential Torque and Speed Control

While there is metal between the rolls, the plain series connection is basically quite satisfactory for a twin drive. When the mill is empty, however, there is nothing to tie the two motors together mechanically, and their speeds may vary widely. In fact, one motor may come to rest and the other run on double voltage, if there is any appreciable difference in their respective light load torques. To avoid this a mid-wire is connected between the two halves of the armature circuit, as shown in Fig. 8. This prevents any difference in voltage across the two motors.

A resistance (not shown) can be connected in this mid-wire circuit to limit any unbalanced load currents during rolling. These may be caused, for example, by a difference in roll diameters and consequently in roll torque.

The Company's own experience and also experience in the United States indicated that so long as the mill motors share the load fairly well no difficulties occur in rolling. It was therefore doubtful if there was any need for special control to give variable ratios of motor torques and speeds, but it was decided to include such control in the Abbey drive, since it was the first large twin drive in this country.

This control is in two parts :—

(*a*) Differential speed control, affecting the relative speeds of the motors when the mill is empty. The ability to adjust this relation may in certain circumstances assist entry of the piece into the mill.

(*b*) Once the metal is between the rolls, the two motors are tied mechanically together. The problem then becomes one of differential torque control.

An obvious method would be to connect the motors in parallel and control the motor fields. The differential speed control could be obtained by making a fixed difference in the motor field excitations. The piece always enters the mill below base speed, so that variations due to saturation effects over the field weakened range would not matter. The differential torque control could be obtained by providing adjustable compounding on the two motors. Controlling the motor fields is not, however, a satisfactory method of obtaining differential torque control. Even with a high degree of field forcing, the rate of response of the motor field circuit is relatively slow. On the

majority of the passes therefore an appreciable proportion of the total length of the piece may have gone through the mill before the desired torque relation has been reached.

As already mentioned, the series connection was considered the preferable basic arrangement, independently of any considerations of torque control, but it also enables a very simple means of differential torque and speed control to be adopted. This is done by means of a small generator connected in the mid-wire circuit, as shown in Fig. 8. Under no-load conditions the voltage of this generator is controlled at a value which is an adjustable proportion of the main generator voltage. This voltage appears as a difference in voltage across the two motors, causing them to run at different speeds. When the piece enters the mill an over-riding control is automatically applied by a control exciter acting on the field of the mid-wire generator. This control keeps the currents in the two halves of the armature circuit at a predetermined ratio. Since the motor fields are equal, the torques are also kept in this ratio. The mid-wire generator is only a small machine, its R.M.S. output being about 50 kW, and hence very rapid control of the relative torques can be obtained. A change-over switch is provided so that the mid-wire generator can be disconnected and replaced by a limiting resistance.

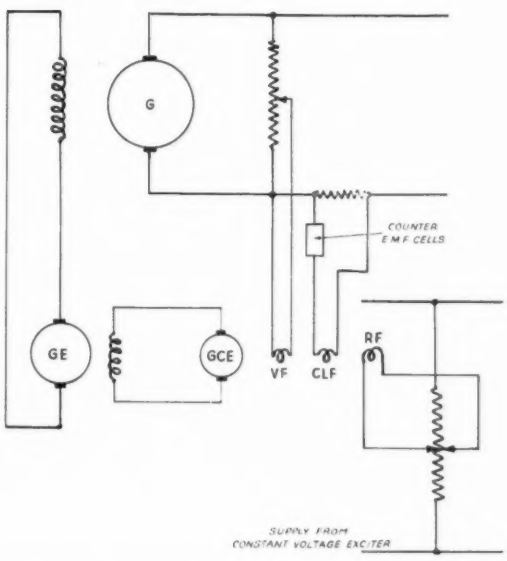


Fig. 9. Elementary diagram of generator control

Scheme of Speed Control

The control scheme for the Abbey Works slabbing mill is basically that used by The English Electric Company on many other reversing mill drives. The differential torque and speed control was at the time peculiar to the Abbey drive but it is now being used on other 'English Electric' twin drives.

As already mentioned, the main features required in a reversing mill drive are rapid response and high torque. The latter is a function of the size of the machines, but the former is largely dependent on the control scheme. To give rapid response the control must be designed to overcome the electrical inertia of the machine fields. The inductance of these fields tends to prevent rapid changes in field fluxes and the voltages dependent upon them.

In addition to providing quick response the control must fulfil one more important requirement. It must provide inherent protection of the drive against mal-operation, and whatever means are adopted for this purpose should have the minimum possible effect on the rate of response.

Fig. 9 shows the basic scheme for generator voltage control, one generator only being shown for simplicity.

The fields of all four generators are fed from one exciter GE. The field of this exciter is in turn fed from a quick response amplifying control exciter GCE, which is of the series self-excited type with special quick response and temperature compensation features.ϕ

The whole of the generator voltage control is carried out by the various fields on GCE, only a very small effective excitation being required from these fields to give full generator volts. Both GE and GCE are so designed that if the necessary extra excitation is applied they will give a much higher voltage than that required to produce full generator volts under steady state conditions. Hence, any appreciable change in the effective

ϕ A more detailed description of this machine will be given in a subsequent article.

excitation of the control fields on GCE produces high voltages from GCE and GE to give a high degree of field forcing and rapid response.

The over-riding control of generator voltage is provided by the reference field RF. This is connected to various taps on a potentiometer by the pulpit operator's master controller, the potentiometer being fed from the constant voltage exciter. The excitation provided by RF is far in excess of that required to enable GCE to maintain the appropriate generator volts, but this excitation is counter-balanced by the voltage feed-back field VF. The ampere turns provided by VF are almost equal to those provided by RF when the correct generator voltage is reached, leaving only the very small difference necessary to maintain this generator voltage.

Thus the action of the control is to produce a generator voltage proportional to the excitation of RF and to maintain the voltage constant at this value. Any change from the correct relationship between RF and VF immediately produces high voltages from GCE and GE to give a large degree of generator field forcing and to change the generator voltage rapidly to the value required to restore the correct relationship. The change may be a return to the same voltage value, the divergence having been due to a change in voltage from the value corresponding to VF, or it may be a change to a new value brought about by a change in the value of RF.

Rapid changes of generator voltage result, of course, in corresponding high rates of acceleration and deceleration of the mill motors. These in turn require high armature currents. When accelerating, these currents, superimposed on those required to produce the rolling torque, may give excessive overloads if the latter are heavy. This could be prevented by reducing the rate of response, but it would involve limiting the rate of acceleration to the value required to prevent overload when the heaviest rolling loads occur, and on lighter loads it would not be possible to use the extra margin of motor torque to give higher acceleration.

Therefore the system adopted is to allow the fastest rate of response to take place until the armature current reaches the working peak value ($2\frac{1}{2} \times$ full load). A rise in armature current above this value automatically changes the generator voltage so that the current is restored to its predetermined peak value.

This action is brought about by the current limit field CLF on GCE. This field is connected across the generator compensating windings so that it is fed by a voltage proportional to the armature current. The circuit of CLF is provided with special means to prevent any current flowing until the voltage across the compensating winding reaches the value corresponding to $2\frac{1}{2} \times$ full load. Counter e.m.f. cells were used for this purpose, their characteristics being such that they pass only a very small current until a certain voltage is reached ; above this voltage the current is limited only by the resistance of the cell, which is low. The cells have no capacity and the action is reversible.

The circuit design is such that at the cut-out current of $3 \times$ full load, the ampere turns on CLF are equal to those on RF. Thus, when rolling, any currents above $2\frac{1}{2} \times$ full load reduce the voltage until at $3 \times$ full load the voltage becomes zero. Although the purpose of this control is mainly to limit currents on acceleration, currents up to $3 \times$ full load may be produced by the rolling torque. If this occurs, the motor stalls and a time delay overload device trips the generator voltage if the stalled condition is maintained for too long.

Fig. 10 shows the basic diagram for the motor field control.

The fields for the four armatures are fed in parallel from the constant voltage exciter CVE. In series with the fields is a bucking exciter BE, by means of which the field current is varied.

This arrangement has three advantages :—

(*a*) Any failure of the source of supply to the mill motor field is also a failure of generator voltage control.

(*b*) If a separate mill motor field exciter is used, a failure of either this exciter or the constant voltage exciter shuts down the mill. With the scheme adopted, a failure of the bucking exciter only prevents the mill being run above base speed.

(*c*) It simplifies the mill motor field control scheme.

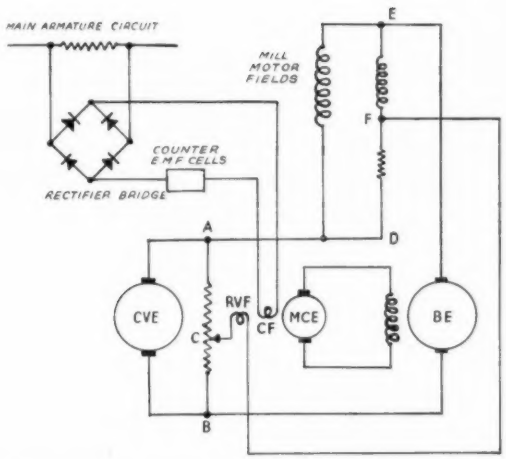


Fig. 10. Elementary diagram of mill motor field control

The bucking exciter is controlled by the control exciter MCE, which is similar to the generator control exciter. The same basic control is used as for the generator, except that the functions of RF and VF (in Fig. 9) are combined in one control field RVF. One end of this field is connected to various points on potentiometer AB by the pulpit operator's master controller. The other end is connected to point F. The circuit DE is a low-current circuit in parallel with the motor fields. It is designed to have the same time constant as the mill motor field circuit so that the voltage DF is proportional to the motor field current under all conditions, both transient and stable.

The control acts to reduce the excitation of RVF to zero. Thus the mill motor field current is varied so as to make the voltage across DF (and also AF) equal to that across AC.

Whereas current limit was introduced in the generator control, compounding is introduced in the mill motor control. The reason is the same, viz., to protect the drive against mal-operation.

Again, counter e.m.f. cells are used to prevent the compounding coming into action before a predetermined current has been reached, in this case $1\frac{1}{2}$ to 2 $\times$ full load. The action of the compounding circuit is very similar to that of the generator current limit circuit, the one major difference being that the compounding field CF is fed through a rectifier bridge. This is necessary as the direction of compounding must be the same for both directions of rolling, i.e., to cause field strengthening. Although this means that the compounding tends to increase regenerative currents when strengthening the mill motor field, other features in the circuits prevent these currents becoming excessive.

In addition to the basic features just described, various others are of course included. In both the generator and motor control schemes feed-back circuits enable the fastest response to be obtained without oscillation of generator voltage or motor field current. Circuits are also provided to enable the rates of response to be adjusted. In the case of the motor, different rates of response can be provided for acceleration and deceleration, since a greater rate of change of flux can be permitted when field weakening than when field strengthening.

Ilgner Motor Control

The control of the Ilgner set driving motor, which operates at 11,000 volts 3-phase 50 cycles, is relatively simple, being concerned only with starting, stopping, and controlling the speed of the set with the load so as to use energy in the flywheel to lessen the peaks on the Ilgner motor.

This control is effected by the combined liquid starter and slip regulator (shown in Fig. 3 on right in background).

Starting of the Ilgner set is automatic upon closing the stator switch. This action starts a D.C. pilot motor which lowers the electrodes of the liquid regulator. The pilot motor does not drive the electrodes down, but only allows them to fall under their own weight. As soon as the stator current reaches the value at which the regulator is set to maintain constant current (as described later), a torque motor takes over and controls the rate of fall so as to give this current.

When shutting down, the set can either be allowed to coast to rest or be braked dynamically. In the latter case the stator is excited from the constant voltage exciter and the slip regulator is used as a braking resistance. An emergency hand brake is provided on the flywheel, and this can also be used as a lifting band for raising the flywheel to allow inspection of the bearings.

The dynamic braking is applied through a control switch on the motor room desk, after the stator switch is opened. Once initiated, the necessary control sequence follows to apply braking automatically. The isolator for the stator D.C. excitation circuit is closed, the pilot motor raises the electrodes to their correct position for braking, and the D.C. contactors close to put the excitation on the stator. The excitation is automatically tripped when the set comes to rest, which takes about 3 to 4 minutes. Shorter stopping times can be obtained if required.

The D.C. stator isolator* is actually an oil circuit-breaker which is mechanically and electrically interlocked with the 11,000 volts A.C. stator switch* to prevent both being closed together.

The object of the control which operates during rolling is to vary the speed of the Ilgner set so as to prevent the peak loads on the 11,000 volt system from exceeding a pre-determined value. This is done by raising the regulator electrodes as soon as this load is reached, and by controlling their position thereafter so as to maintain this load constant until they return to their lowest position. Thus when a heavy load is imposed on the Ilgner set by the mill motors, and then removed, the sequence is as follows :—

(*a*) The load on the 11,000 volt system rises until it reaches the pre-determined peak value. The control is arranged so that this can be adjusted over a range between 85% and 120% full load of the Ilgner motor.

(*b*) When the load reaches the pre-determined value the regulator electrodes are raised, increasing the rotor resistance and causing the speed of the set to drop. This allows energy to be taken from the flywheel to provide the additional power required by the mill motors. So long as the load on the Ilgner set persists, the electrodes will continue rising so as to allow a continued output of energy from the flywheel.

(*c*) After the load is removed from the Ilgner set, the electrodes fall at the rate required to maintain the pre-determined peak. During this time the Ilgner motor is putting energy back into the flywheel and re-accelerating the set.

* *Not supplied by The English Electric Company.*

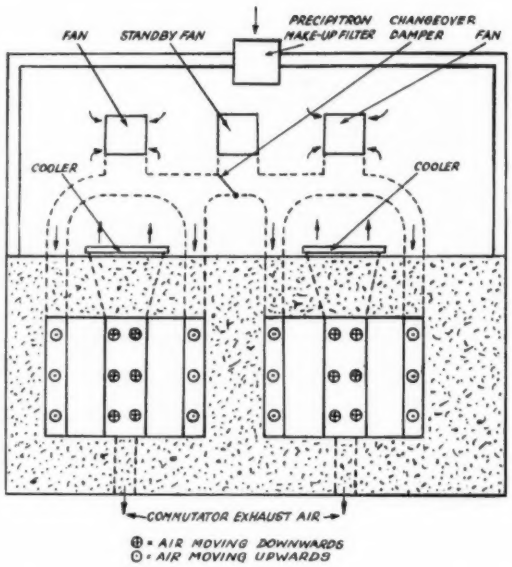


Fig. 11. *Schematic layout of mill motor ventilation system*

The electrodes continue to fall until either they reach their lowest position or another load comes on the set.

The control of the electrodes is achieved by a torque motor supplied from a 3-phase series transformer in the Ilgner motor stator circuit. The torque of this motor acts against the out-of-balance weight of the electrode system which tends to hold the electrodes in. Taps on the series transformer enable its ratio to be varied.

Ventilation

With equipments the size of the Abbey Works drive, ventilation is of prime importance. There are two basic problems :—

(*a*) Cooling the mill motors. Since these are slow running machines they must be forced ventilated.

(*b*) Maintaining a reasonable temperature in the motor room. For this some form of ventilation is necessary for the large naturally-ventilated machines as well as the mill motors.

Various methods were considered but a re-circulating scheme was finally adopted using two self-contained systems, one for the Ilgner set and one for the mill motors. In the case of the mill motors and generators, air is blown in at the non-commutator end of the armatures and collected at the commutator end for re-circulation through coolers. On the Ilgner set driving motor, the air is blown in at both ends and discharged through a bottom chimney. Figs. 11 and 12 show these systems in sketch form.

In a self-contained re-circulating system for a group of machines situated close together, the path taken by the air is usually short and the air speed is high compared, for example, with a re-circulating system which includes the motor room. If the commutators of D.C. machines are included in the system, carbon and copper dust will enter the air stream. The short path and relatively high air speed will give very little opportunity for this dust to be deposited before the air re-enters the machines. In fact, the majority of any such deposit will occur in the air coolers and affect their efficiency. It is therefore most desirable to prevent this dust entering the coolers or the machines.

To provide a filter to remove such fine dust and handle the whole of the air quantity is impracticable from economic and space considerations. Special enclosures are therefore provided over the commutators of the D.C. machines, arranged to collect the majority of the air leaving the machine before it reaches the commutator ; this air is re-circulated.

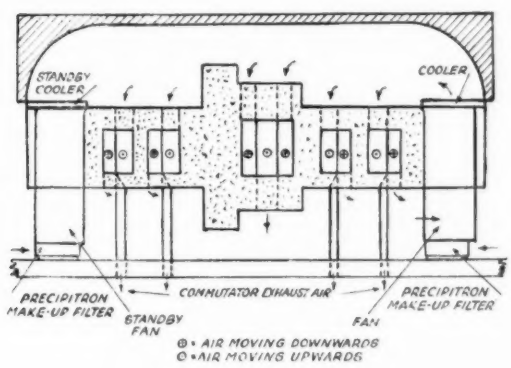


Fig. 12. Schematic layout of Ilgner set ventilation system

The remainder of the air (about 10 to 15%) passes over the commutator, is collected separately and expelled from the machines and motor room. Fig. 13 shows the commutator enclosure of one of the generators. The air entering the enclosure, which contains the dust formed at the commutator, is taken through a duct and exhausted to the slab yard which runs adjacent to the motor room.

Make-up air is introduced through Precipitron type electrostatic filters which prevent dirt entering the re-circulating system, and axial flow fans mounted in the commutator exhaust ducts establish the correct direction of air flow. The make-up air is drawn from the motor room basement which is already supplied with electrostatically filtered air from the separate motor room ventilation system.

The ventilation equipment was sub-contracted to Messrs. Matthew & Yates, for whom Messrs. Heenan & Froude made the coolers.

Lubrication

Three systems of lubrication are involved :—

(*a*) A pressure system for the mill motor and 'A' frame bearings.

(*b*) A flood system for the Ilgner set machine bearings and the mill motor thrust bearings.

(*c*) A pressure system for the flywheel bearings.

It was decided to adopt a centralised scheme as far as possible, rather than individual units, the flywheel being excluded for reasons given later. Before describing the scheme as a whole, the principle of operation of the three basic systems is outlined.

MILL MOTOR LUBRICATION

Each mill motor bearing and also the 'A' frame bearing are lubricated at a pressure of between 150 and 250 lb per sq. in. A separate pump and a standby pump are provided for each bearing, the four pumps for each motor being arranged in two double pump sets, one running and one standby. The two pumps of each set are coupled to opposite ends of a totally enclosed squirrel cage induction motor. The two 'A' frame pumps are arranged as two single pump sets.

Each of the five bearings is equipped with a pressure gauge, pressure relay, dial type thermometer and thermostat. The control is interlocked so that the drive cannot start unless the correct oil pressure has been built up. When the drive is running, a maintained fall in oil pressure below a minimum value will stop the mill when the driver brings his controller back to the 'off' position; that is, it will stop the mill at the end of a pass and not whilst metal is in the rolls. A fall in oil pressure below the minimum also automatically starts-up the appropriate standby pump set. If this restores the oil pressure, the drive will not trip out, but an alarm is given to inform the motor room attendant that oil pressure has failed.

Contacts on each thermometer operate an alarm if the bearing temperature becomes too high, and if the temperature continues to rise the thermostat operates to trip the drive.

The oil from the mill motor journal and thrust bearings combines in a common outlet pipe in which a flow relay is connected. Failure of oil flow operates an alarm.

Flood Lubrication

The five machine bearings of the Ilgner set and the four mill motor thrust bearings are flood lubricated by oil supplied from a gravity tank in the roof, each bearing being supplied through a separate pipe. Oil is supplied to the gravity tank by a single pump driven by a squirrel cage induction motor. A standby pump set is provided and is automatically started by a float switch if the oil level in the gravity tank falls below normal. The float switch also operates an alarm. Each pump supplies slightly more oil than is required by the bearings, so that a continuous overflow is provided from the tank. The overflow pipe is capable of taking the full output of both pumps so as to minimise the possibility of oil flowing over the top of the tank. This arrangement is considered preferable to the alternative of maintaining the oil level by start-stop control of the pump through the action of a float switch.

Flywheel Lubrication

The two flywheel bearings are pressure lubricated by separate pumps, belt driven from the flywheel shaft. A standby electrical pump set takes over automatically if the mechanical pumps fail, and is also used during the starting and stopping periods as at low speeds the mechanical pumps do not deliver sufficient oil. This system ensures an oil film in the bearings even at standstill and is particularly advantageous when starting.

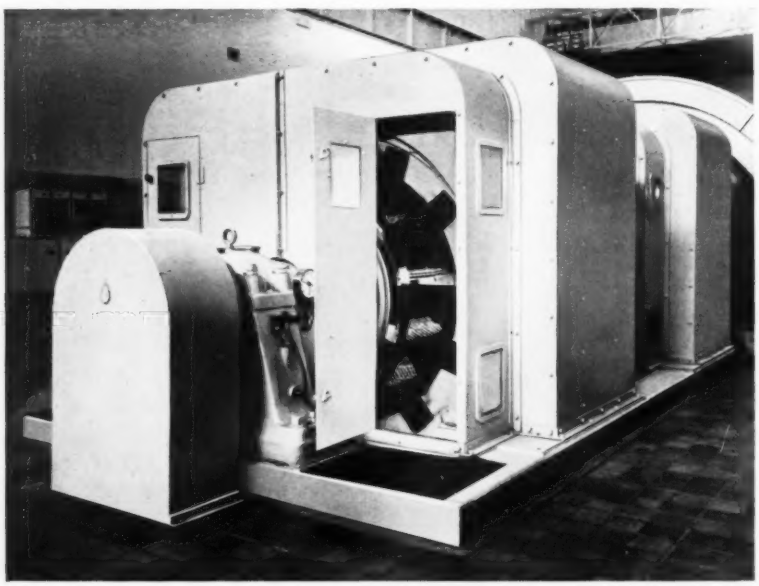


Fig. 13. *Generator commutator enclosure*

The flywheel equipment was manufactured for The English Electric Company as a complete unit by Messrs. Hick, Hargreaves & Co., Ltd. As mechanically driven pumps were considered essential to maintain lubrication of the flywheel bearings in the event of a complete power failure, it was decided to make the flywheel lubrication a completely separate self-contained system. Pumps, reservoir and coolers are all contained in the flywheel bedplate, the electrically driven pumps being coupled through shafts to a squirrel cage induction motor situated between the two legs of the bedplate.

An oil pressure gauge, oil pressure relay, dial type thermometer and a thermostat are provided for each bearing. The Ilgner set cannot be started until the flywheel bearing oil pressure has reached the correct starting value. After the set has started, should the oil pressure fall below the correct running value the electrical pump set is automatically started. If the oil pressure is not restored within a predetermined time, the Ilgner set is automatically stopped by dynamic braking.

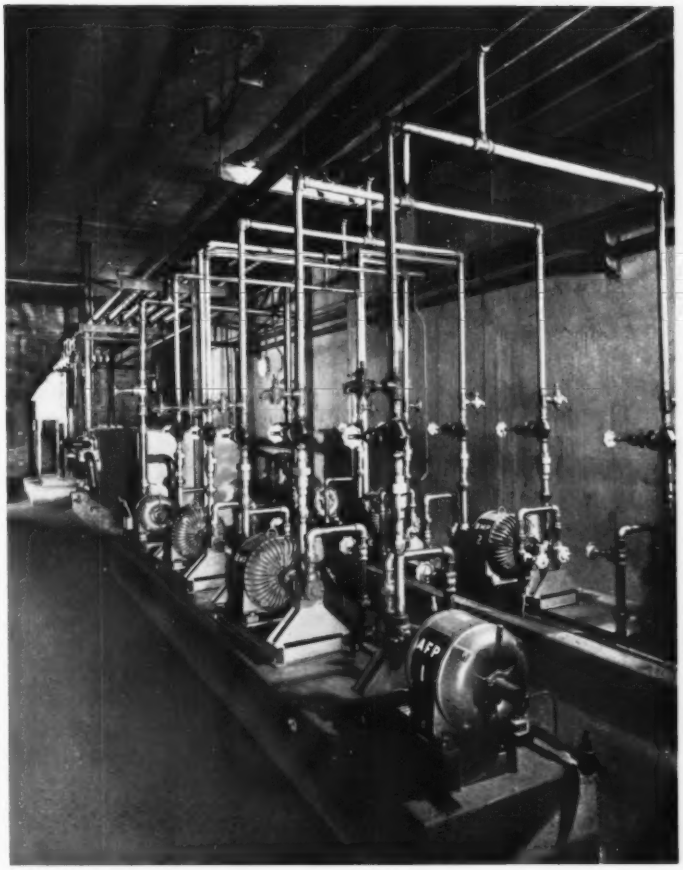


Fig. 14. *Lubrication room*

Contacts are provided on the thermometers to initiate an alarm if too high a temperature is reached. If the temperature continues to rise and becomes dangerously high, the thermostats operate automatically to shut down the set on dynamic braking. Oil flow relays were not provided as there was insufficient head of oil from the bearing outlet to give satisfactory operation. It was considered undesirable to fit such relays on the pressure side of the bearing due to the increased possibility of oil leakage.

Centralised Lubrication Scheme

As already mentioned, the centralised scheme covers the lubrication of all bearings except the two flywheel bearings. The equipment is housed in a separate lubrication room (Fig. 14) situated along the outer wall of the cool air chamber for the Ilgner set.

Oil from each bearing returns through a separate pipe (mill motor journal and thrust bearings have a combined outlet) to a return trough which is contained in a totally enclosed housing provided with a Perspex window and internal illumination ; the housing can be seen in Fig. 14 mounted on legs at the far end of the lubrication room. Each return pipe runs into a separate tundish from which the oil flows over a ' V ' notch into the trough proper. Separate returns allow samples of oil

from each bearing to be taken, and the 'V' notches provide a ready indication of the amount of oil flowing. In addition, a flow relay is connected in each return pipe, just above the trough. Each relay initiates an alarm if the oil flow falls too low

The oil flows from the trough to a 'warm' reservoir tank whence it is pumped through a cooler into a 'cool' reservoir tank. A standby cooler and pump are provided and an oil flow relay effects automatic changeover if one equipment fails. In addition, a balancer pipe between the two tanks prevents stoppage of oil flow should both cooler circuits fail.

Two bus pipes from the 'cool' reservoir feed the various pumps, one pipe feeding the No. 1 pumps of each pair and the other pipe the No. 2 pumps.

Oil is delivered to the bearings as already described. A filter is provided at the inlet to each bearing, mainly for use during commissioning and after a shut down.

A centrifuge is permanently mounted in the lubrication room and connected to the reservoir tanks, and periodic cleaning of the oil is included in the maintenance routine.

Feed Rolls Drives

The rollers leading into and away from the slabbing mill are driven in groups through bevel gearing, with the exception of the two pairs of rolls immediately adjacent to and on either side of the mill rolls. These two pairs of feed rolls are each driven by a separate motor through a gear reduction unit with twin output shafts and universal spindles. The two motors are each rated at 50 h.p. 550 r.p.m. 230 volts, and are forced ventilated so that this rating is continuous.

The possibilities were considered of running the feed rolls in synchronism with the mill rolls or with the appropriate table rollers, or of providing means for doing either. It was finally decided to run them in synchronism with the mill only, and the drives together with the associated Ward-Leonard control were supplied by The English Electric Company as a part of the main drive equipment.

Each motor is fed from its own variable-voltage generator, the two generators being mounted at opposite ends of the main exciter set. Links are provided to enable both motors to be run in parallel off one generator.

The main duty of the feed rolls is performed when the piece is entering and leaving the mill, i.e. at low speeds. It was therefore decided to control the motors by armature voltage up to the speed corresponding to mill base speed. Above this, the fields of the feed roll motors are weakened so that their speeds match the mill speed.

The voltage control is basically the same as that for the main drive, except that in the case of the feed roll drive the generator field is excited directly from the control exciter. Also the counter e.m.f. cells are replaced by a magnetic amplifier circuit. The field weakening control is effected by inserting steps of resistance in series with the motor field.

The feed roll control exciters are mounted at opposite ends of the main drive control exciter set.

Conclusion

The slabbing mill went into operation in November 1950, since when it has been operating successfully. The present energy consumption of the main drive without auxiliaries is about 8 to 9 kWh per ton.

Other equipment supplied to the Abbey Works by The English Electric Company will be described in a subsequent issue of this journal.

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The Internal Combustion Engine and Jet Propulsion Applied to Aviation

By A.W. Morley, Ph.D., M.Sc., A.C.G.I., A.F.R.Ae.S., D. Napier & Son Limited.

MODERN ENDEAVOUR to fly may be considered to have started with the Italian, Leonardo da Vinci, who 450 years ago planned a system of mechanically controlled wings moved by muscular power. It was not until the introduction of the internal combustion engine that it was possible to construct a machine which could carry a pilot in sustained flight. Wilbur Wright, an American, the first man to fly, did this successfully in 1903. To-day aviation plays an essential part in world government and in our lives ; the ease of rapid transit throughout the world is effecting a revolution in our ways of thought as profound as that which followed the introduction of printing into Europe in the middle ages.

The essence of flight is that it makes possible rapid and easy transport over all the old geographical barriers, and its most important asset is high speed. The rapid development of the internal combustion engine, and the discovery that this form of prime mover is ideally suited to the task, has made high-speed flight a commercial possibility. The graph in Fig. 1 shows the progress in the top speed record since flight began at the beginning of this century.

The prime-mover of a flying machine must be light, or too much of its power is expended in sustaining its own weight : it must be economical in fuel consumption, and it must have a very small frontal area so that little of its power is wasted in overcoming head resistance and body drag. These essential requirements are the special attributes of the internal combustion engine.

The motor used by the Wright brothers in 1903 was a 30 b.h.p. 4-cylinder engine weighing 210 lb, and driving two 8 ft propellers it produced about 75 lb of thrust. A modern Rolls Royce Avon jet engine produces 6,500 lb of thrust for 2,250 lb of weight and gives its thrust directly by jet reaction without a propeller. These two classical examples represent more than an 8-fold improvement in engine thrust/weight ratio, due in part to the rapid development of the flying machine under the stimulus of two major wars, and the advent of the turbo-jet engine made possible by the introduction of the gas turbine.

Essentially, all aero engines generate thrust by jet reaction. In the older piston propeller engines the propeller power generates a rearward flowing jet of air whose reactive force is measured by the momentum of the slip stream, i.e. the product of the mass of air per second passing through the airscrew disc and the change in velocity of the air as it passes through the disc. This change of momentum per second is equal to the forward thrust of the engine. Whittle, when his first

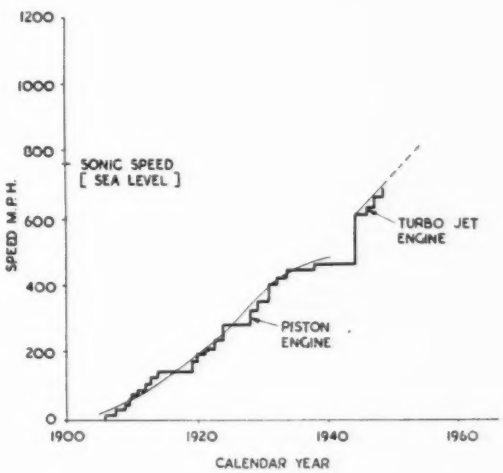


Fig. 1.—Sea level speed records for aircraft

engine flew in 1940, demonstrated how a powerful thrust could be obtained from the exhaust of a gas turbine without the complication of pistons, crankshaft and geared propeller, and therefore with a much simpler and lighter mechanism than ever before.

The Principle of Jet Propulsion

As already stated, the propulsion effort of an aero-engine is generated essentially by jet reaction, although the prime mover has different forms depending upon the particular adaptation of the internal combustion principle. If a jet of air, or exhaust gas, is discharged rearward at velocity Vj ft/sec, the mass of air or gas so discharged being Q lb/sec, then the thrust obtained is $\frac{QVj}{g}$ lb. If the air is received into the engine at a flight speed V ft/sec, some of the useful thrust is expended in overcoming the momentum of this air. The net thrust is then simply the net change in momentum $\frac{Q(Vj-V)}{g}$. Here it is assumed that as much exhaust is expelled per second as fresh air is drawn in ; this is not quite true because the fuel has been added to the air as it passes through the propulsive unit.

In a propeller engine the thrust is still generated by jet reaction and is again equal to $\frac{Q(V_2-V_1)}{g}$, where Q is now the air mass flow rate through the propeller disc and V_1 and V_2 the approach and leaving velocities at the disc respectively.

It is always important in aeronautics to design for the highest possible efficiency, and simple direct jet propulsion is limited to a fairly low efficiency because all the kinetic energy $\frac{QVj^2}{2g}$ in the jet is dissipated. On the other hand a propeller can be highly efficient because for a given engine power it deals with a much greater mass of air, discharging it with a relatively low increase in speed.

The kinetic energy $\frac{QVj^2}{2g}$ is the energy of motion which must be supplied to the mass Q within the engine in order to send it rearward at velocity Vj ; similarly $\frac{QV^2}{2g}$ is the energy of motion received with the air entering the engine. The energy of motion required to produce the propulsive jet is therefore $\frac{Q(Vj^2-V^2)}{2g}$. The useful work obtained from the jet is the product of the thrust and distance moved through per second, i.e. $\frac{Q(Vj-V)V}{g}$. Hence the efficiency of the jet as a means of propulsion is

$$\eta = \frac{\frac{Q(Vj-V)V}{g}}{\frac{Q(Vj^2-V^2)}{2}} = \frac{2}{\frac{Vj}{V}+1}$$

It can be seen that V must be nearly equal to Vj for the propulsive efficiency to approach 100%. At low aircraft speeds the most efficient means of propulsion is a propeller because the delivery velocity Vj of the airscrew need not be very much greater than the flight speed V, whereas, if all the gases pass through the engine, V_j must be higher in comparison and therefore the propulsive efficiency lower. For high-speed flight however, with the efficiency $\frac{2}{Vj/V+1}$ increasing as V increases, the pure jet is better than the propeller above a certain speed. The propulsive efficiency of the jet is obviously one of the most important factors affecting jet propulsion.

The kinetic energy $\frac{QV_j^2}{2g}$ is put into the tail jet as the result of the thermodynamic process within the engine and is obtained from the chemical action of the fuel and a supply of oxygen. When the oxygen is obtained from atmospheric air the combustion reaction will be diluted by a certain proportion of inert atmospheric gases which are usually essential to limit the temperature of combustion to a value which can be safely sustained by the combustion chamber and mechanical parts of the engine. This applies particularly to the turbo-jet and turbo-propeller cycles where there is considerable excess of air beyond chemical requirements. In the piston engine and ram jet the air need not be in much excess. The inert nitrogen then acts as the diluent sufficient to limit combustion to a safe intensity. In the rocket motor the oxidant is carried with the fuel and sometimes there is no diluent at all, so that the highest possible

temperatures are produced. Only the absence of any moving parts subjected to the direct heat of the combustion reaction makes such a system possible.

Propulsive Systems

PISTON ENGINE

The first successful aero-engine was the multi-cylinder petrol piston engine. In this the cylinder and moving piston form the sealed combustion chamber, where the release of chemical energy takes place practically at constant volume. The cylinder is usually supercharged by a blower, which may be driven through gearing from the engine crankshaft. The propeller is driven through a speed reduction gear. Besides the thrust obtained from the propeller a useful additive thrust, perhaps 10%, is obtained from the exhaust jets of the cylinders which are directed rearward for this purpose.

There are several variations of the simple piston engine depending principally on whether the cylinder is liquid-cooled with a radiator or air-cooled, and whether poppet valves or sleeve valves are employed. All existing simple piston engines use the 4-stroke cycle with spark ignition and burn a petrol fuel of high 'anti-knock' value to avoid detonation. Although piston engine technique is very highly developed there is still great variety in detail, showing that design is not yet finalised.

In commercial aviation the piston engine has advanced further in America than in any other country. It has reached a high degree of excellence coupled with an exhaust driven turbo-supercharger which improves power at high altitudes, reduces fuel consumption and also helps to silence the exhaust. Mainly due to the question of size, the forward trend of design has been much slower since the advent of the gas turbine. Passenger carrying aircraft tend to get larger and thus require bigger engines. The limit of the piston engine seems to be about 3,500 b.h.p. per unit, which is a moderate size for a propeller turbine engine.

PROPELLER TURBINE ENGINE

In the propeller turbine engine (Fig. 2) air is compressed in 10 or more stages depending on the pressure ratio of the design, which will be of the order 6 to 1, and enters the combustion chamber in a steady flow. The fuel is there finely mixed with the air and is burned at nearly constant pressure, thus producing a large increase in the volume of the gas. After combustion the hot gases pass into the turbine where they expand down to exhaust pressure which is practically atmospheric. The turbine drives the compressor, and a propeller through reduction gears. A useful additional jet-thrust is obtained by the momentum discharged in the tail pipe, and is of particular value at high speeds because it maintains its full thrust effect while the propeller thrust power falls off due to the drop in propeller efficiency which occurs at high forward speed.

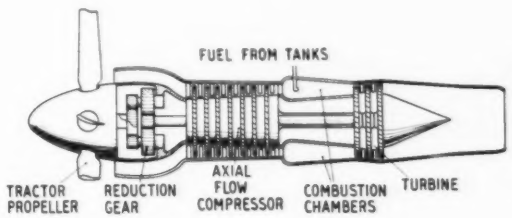


Fig. 2.—Propeller turbine engine

Though this type of engine appears simple essentially, it is not easy to reach the necessary standard of reliability. If the propeller turbine is to supplant the piston engine, an even higher standard of reliability is desirable than was commonplace with the piston engine. The progress since the 1939-45 war on some British propeller turbines is extremely encouraging.

The propeller turbine is probably the form of engine which will ultimately be used for the bulk of the middle distance and long distance air traffic. It is lighter than a piston engine, has the good performance at take-off inherent in a propeller, and the fuel consumption at moderately high speeds (350 m.p.h.) is better than that of the piston engine. Performance improves with an increase in the turbine operating gas temperature, so that full use can be made of any future improvements in material properties at high temperatures. The engine has no reciprocating masses to give rise to vibration, and it is reasonably simple mechanically.

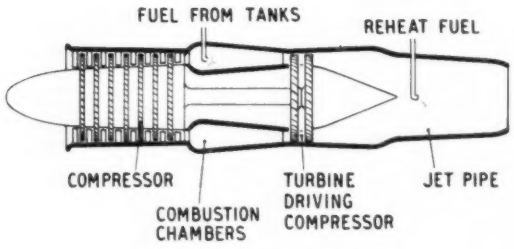


Fig. 3.—Turbo-jet engine

Moreover the optimum flight speeds for the propeller turbine, although above those of the piston engine, are not so high as to be too costly or to make unreasonable demands on airline facilities.

Turbo-jet Engine

The simplest and most popular gas turbine engine to-day is the turbo-jet (Fig. 3). The compressor and turbine are coupled together on one shaft with the combustion chambers interposed. The turbine is so designed that the expansion and heat drop in it produces just sufficient power to drive the compressor and small auxiliaries, leaving some total head pressure for the final expansion in the tail pipe. The exhaust gases leave the turbine at a high axial speed which is further increased in the final propelling nozzle. All the available energy from the internal combustion cycle is used to give kinetic energy to the final jet. The higher the temperature in the turbine the greater the energy generated, the higher the jet velocity, and the greater the thrust. However, the increased kinetic energy dissipated is usually reflected in a poorer specific fuel consumption.

The great merit of the turbo-jet engine for aircraft propulsion is its relative simplicity, light weight and low frontal area. The fuel economy is not so good as that of the propeller turbine, except at high speeds when the thrust efficiency of the propeller falls off and the extra weight of the propeller and reduction gear begins to tell. The turbo-jet engine is ideal in the very high transonic speed class of military aircraft, and with the introduction of the high speed high altitude passenger aeroplane it is coming into use for civil transport purposes.

Composite Engine

The composite engine (Fig. 4) combines the high power-generating qualities of the gas turbine with the efficient combustion and high torque-producing qualities of the piston engine. In the form shown the axial compressor receives the atmospheric air and passes it to a centrifugal compressor which is coupled to a multi-cylinder reciprocating power unit in which combustion takes place practically at constant volume. The exhaust from the piston unit, which is at a suitable temperature, passes through a power turbine coupled to the shaft of the axial compressor. The turbine shaft and the crankshaft of the piston unit both develop a useful power output which is absorbed in a propeller. Additional thrust is developed in the tail jet. The overall expansion ratio is very high, and the cycle has probably the highest thermal efficiency attainable within the sphere of aeronautics, with the result that the engine has a very low fuel consumption per b.h.p. developed.

An engine designed for the composite cycle will have several features not common at present in aeronautics. For example, the air-consuming qualities of the ordinary 4-stroke engine are insufficient to match those of the turbine ; consequently a 2-stroke unit is desirable, as otherwise the bulk of the piston unit is too large for a given horse-power. The detail arrangement of the engine also needs skilful design if it is not to be too heavy, despite its low fuel consumption. A successful engine of this type represents a valuable step forward, since its fuel economy will greatly extend the endurance of present-day aircraft and reduce the cost of long stages. The Napier ' Nomad,'

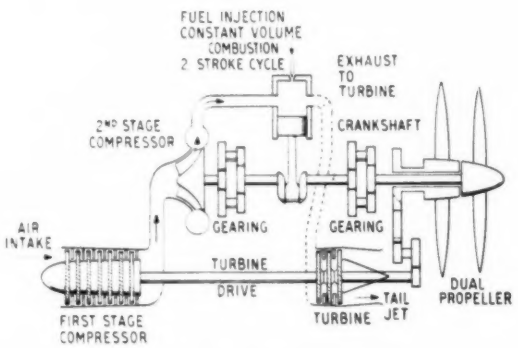


Fig. 4.—Composite engine

which was flown for the first time in 1951, is a 3,000 b.h.p. composite engine.*

Although the composite type engine is not suitable for the very high flight speeds of the turbo-jet, low specific fuel consumption is very desirable in aeronautics. The carrying of adequate fuel reserves to meet such contingencies as bad weather, faulty navigation, head winds and engine failure will be a much less serious problem with the composite than with the turbo-jet engined aeroplane.

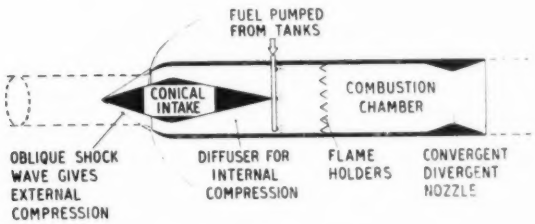


Fig. 5.—Ram-jet engine

Ram-jet Engine

The ram-jet engine (Fig. 5) is the simplest air-consuming power unit so far conceived with a definite application to aircraft propulsion. It has no mechanical compressor, and depends on the ramming effect of the forward speed to compress the air in the intake duct and raise the pressure in the combustion space in the middle chamber of the engine. The intake compression forms the first stroke in the thermodynamic cycle ; the combustion at approximately constant pressure is the second ; the third stroke is the expansion of gases in the jet pipe down to atmospheric pressure ; the fourth and final stroke is the diffusion of the exhaust products in the atmosphere at constant pressure to the temperature of the surroundings. The thrust is obtained purely by jet reaction.

A Frenchman, René Lorin, invented the ram-jet in 1913 but flight speeds at the time were not fast enough to give sufficient compression for a satisfactory cycle efficiency. During the last war, with much higher flight speeds in view, the Germans brought the ram-jet to the early flight stage. With the advent of supersonic flight, the initial problems of which have been solved by means of the turbo-jet and rocket, it now becomes possible to achieve suitable efficiencies from the ram-jet cycle, so that the other advantages of extreme simplicity and high thrust per unit frontal area possessed by the ram-jet may be exploited.

One factor which has held up the introduction of the ram-jet is that it cannot develop thrust until it attains a high forward speed ; consequently there is no thrust for take-off and it is impossible to start the motor in the static condition. Some assisting device such as a take-off rocket or catapult aircraft must be used to launch the ram-jet. It has been predicted that the best speeds for the ram-jet are above a Mach No. of 1.5, i.e. about 1,100 miles per hour and upwards, and this engine may well be the means by which prolonged flight is first attained at supersonic speeds. Because it is an air-consuming engine, its application is limited to altitudes of not more than about 15 miles above the earth.

The application of the ram-jet in the civil field is still uncertain, although of all the internal combustion engine applications to jet propulsion it holds most prospect for the longest ranges at the very highest speeds in the atmosphere.

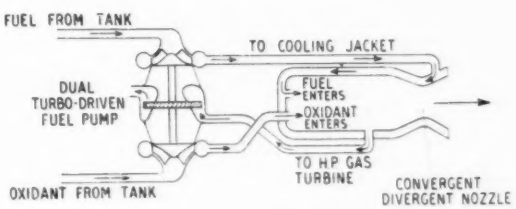


Fig. 6.—Rocket engine

One interesting contemporary application in America is to the helicopter, where the ram-jet units are carried at the extremities of the rotor blades facing the way of rotation. Once the rotor has been started and the speed at the blade tips is high enough, the ram-jets produce sufficient thrust to lift the machine. With this system there is no torque reaction at the rotor head, which permits considerable structural simplification.

* This engine was briefly described in the March 1952 issue of this journal, Vol. XII, No. 6.

Rocket Engine

The final example of the application of the internal combustion principle to aeronautics is the liquid fuel rocket engine (Fig. 6). The essential feature of the rocket motor is that it carries its oxidant with it in tanks, either separately or combined with the fuel, and is therefore independent of the atmosphere. In fact, without any atmosphere, as at extreme altitudes, it works more efficiently because the greater expansion ratio then obtainable produces a higher jet velocity and therefore a greater thrust for the same amount of fuel.

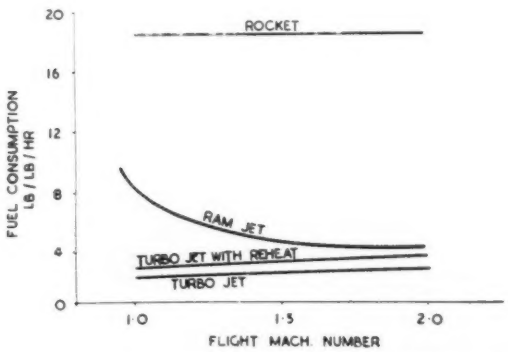


Fig. 7.—Relative specific fuel consumption of turbo-jet, ram-jet and rocket engines

The oxidant is a liquid which will readily decompose in the combustion chamber and set free gaseous oxygen for burning the fuel. Fuel and oxidant are forced separately into the combustion chamber, by such means as a turbo-pump driven by decomposed oxidant or high-pressure gas from the main combustion chamber. Either the fuel flow or oxidant flow may be used to cool the chamber, depending upon the nature of the liquids.

The Germans made outstanding technical advances with liquid fuel rockets during the last war, their greatest effort being the ' V2 ' which generated about 62,000 lb of thrust. The ' V2 ' used alcohol as fuel, liquid oxygen as oxidant and hydrogen peroxide decomposed to steam for driving the pumps. The 'Messerschmitt 163' interceptor aircraft, which could climb to 40,000 ft. in 2½ minutes with a pilot and armament, used hydrogen peroxide as oxidant with hydrazine hydrate and alcohol as fuel.

To obtain rapid ignition the substances used for rocket fuel must be mutually explosive. This can introduce a certain hazard into rocket development work. Such dangers are accepted as commonplace under the stimulus of war, which explains in part the rapid development of the rocket by the Germans.

The rocket has a very high specific fuel consumption per lb of thrust when compared with the turbo-jet and ram-jet (Fig. 7). Thermodynamically the rocket cycle is quite efficient because it has a high expansion ratio, but the propulsive efficiency is poor because of the excessive kinetic energy dissipated in the jet. The engine itself is very light, weighing about one ounce per pound of thrust developed compared with 5 ounces for the turbo-jet, but this advantage is offset by the great weight of fuel to be carried. As a power plant for present purposes its use is restricted to cases where a high thrust is required for a very short duration only.

Fields of Operation

For the more immediate future, the turbo-jet, turbo-propeller and composite engines are of most general interest. These three forms of internal combustion engine have different operating characteristics regarding thrust, fuel consumption and specific weight, which in turn decide the most suitable class of aircraft for the type of engine. Since the essence of flight is speed, a most important factor is the effect of speed on the distribution of

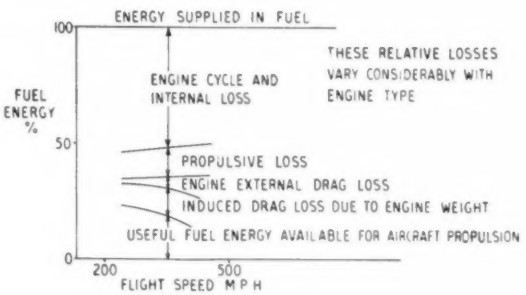


Fig. 8.—Distribution of available energy liberated from fuel by combustion, indicating effect of speed

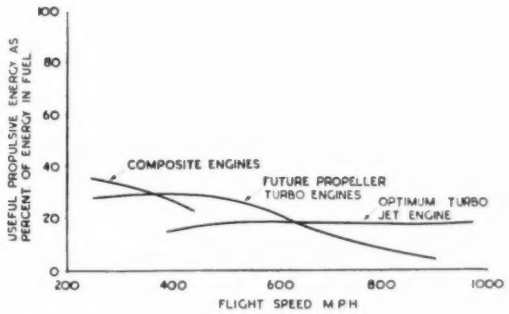


Fig. 9.—Predicted effect of flight speed on useful propulsive energy

available energy liberated from the fuel by combustion. Some of the fuel energy disappears in the losses inherent in the heat engine cycle ; some is lost in kinetic energy of the jet ; more is absorbed in wind resistance and still more in lifting the weight of the engine (Fig. 8). The remaining energy is the useful thrust power, which is available for propelling the aeroplane, its crew, fuel load, and useful cargo.

It is possible to estimate the useful propulsive energy for the different engines (1), and for the speed range from 250 to 1,000 miles per hour it is predicted on certain assumptions that the percentage of fuel energy available to propel an aircraft falls from 35% to 18% approximately (Fig. 9), so that the process gradually gets more wasteful as speed increases. At the low-speed end the most efficient means of propulsion in terms of fuel expended is the composite engine ; over the middle-speed band it is the turbo-propeller and at the high speed end the turbo-jet. This conclusion is broadly correct although the exact cross-over points in the investigation are not fully significant as a way of defining the limits of each type of engine, because they do not take into account relative take-off performance, the premium on speed, maintenance costs, etc., which affect the useful rôle of an aeroplane.

Any attempt to predict attainable limits in aeronautics is open to criticism, because in its short history the internal combustion engine has repeatedly opened up new horizons. It appears, however (2), that an enveloping curve can be drawn having roughly the form of a rectangular hyperbola which indicates the possibilities of the internal combustion engine (Fig. 10). The rocket engine approaches most nearly to the short-range high-speed asymptote, and the composite engine to the low-speed long-range asymptote. Presumably we reach the useful high-speed limit when an aircraft with a rocket motor can attain escape

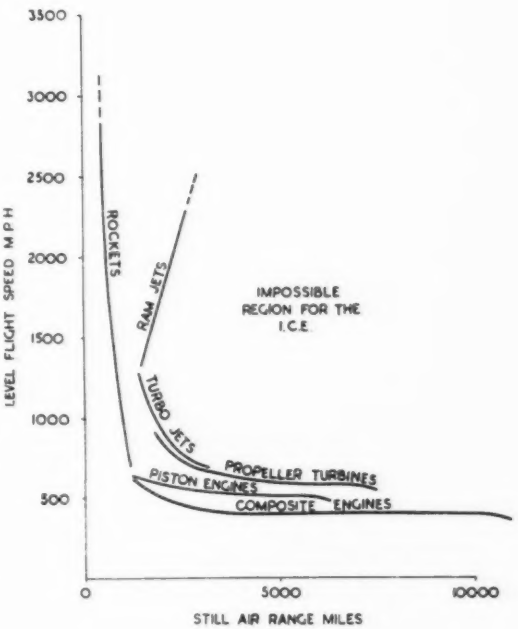


Fig. 10.—Approximate limits of aircraft application of the internal combustion engine

velocity, and the long range limit when composite engined aircraft can encircle the world non-stop. At present it is thought that both these achievements will need a more powerful supply of energy than the chemical energy which can be set free in the internal combustion engine.

(1) See Farrar and Johnson, Aeronautical Engineering Review, July 1950, page 32.

(2) See Shell Aviation News, May 1950.

The Tay Ferry Motor Vessel "Scotscraig"

By N. P. BLACKBURN, A.M.I.Mech.E., M.I.Mar.E., Manager, Marine Projects and Contracts.

THE TAY FERRY M.V. "SCOTSCRAIG" (Fig. 1), commissioned in August 1951, is the result of collaboration between The Dundee Harbour Trust, Caledon Shipbuilding and Engineering Company and The English Electric Company.

The specification of any vessel and its machinery is based upon the requirements of the service for which it is intended and, in its final form, is usually a compromise between the ideal and what is a practical solution to the variety of problems which arise in engineering the project. An indication of this appears in the description which follows.

This ferry service carries the East Coast Highway traffic between Dundee and Newport ; the schedule is rigorous and must be regularly maintained in all weather conditions. The owners required a vessel built to the highest standards and equipped in accordance with the latest practice, and the importance of the service emphasised the need for reliability and maximum availability. As a result of local conditions awkward problems arise from:—

1. Strong tides and high winds which make navigation difficult at certain times in the year.
2. Obstruction of the course by sandbanks which make it necessary to take a U-shaped track between the terminals.
3. The approach on the Dundee side which is awkward and shallow.
4. The existing terminals which were built when traffic was lighter and the vessels were in consequence smaller than they can be to-day.

The direct method of overcoming the difficulties outlined in 2, 3 and 4 was to dredge the channel and maintain it, and rebuild the terminals. On the grounds of costs alone this work could not be undertaken, so that the vessel had to be capable of operating under existing conditions. This requirment imposed severe limitations on the salient

Fig. 1. *The Tay Ferry M.V. "Scotscraig"*

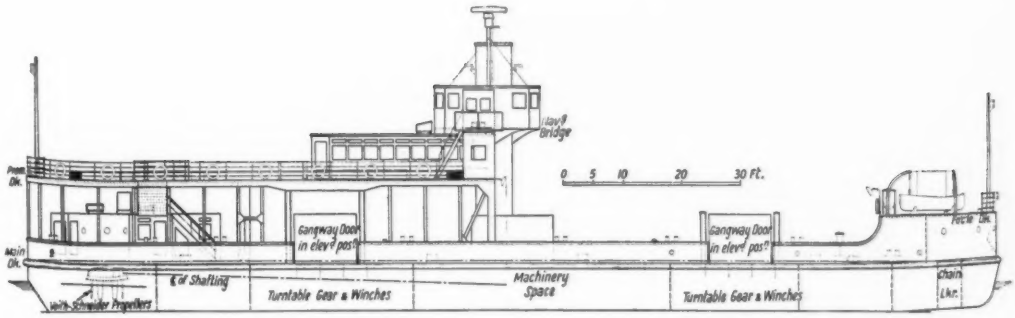


Fig. 2. Profile and hull arrangement of "Scotscraig"

dimensions of the vessel, the depth of the hull at the midship section and its draft being most affected.

When the "Scotscraig" was in project, the service requirements were considered in conjunction with experience with the M.V. "Abercraig," a diesel driven vessel built for this service and equipped with Voith-Schneider cycloidal propellers. On this basis the following particulars were established for the new vessel :—

Length overall	168 ft.
Breadth extreme	50 ft.
Depth moulded	8 ft. 3 in.
Speed	10.5 knots.

Accommodation for 800 passengers to Ministry of Transport Regulations.

A deck space approximately 114 ft. × 40 ft. to accommodate lorries and cars.

The deck area allocated to traffic precluded the provision of a casing for the machinery space and allowed only for a small oval access trunk 14 ft. × 5 ft. 6 in. The machinery had therefore to be accommodated entirely below deck level, in a maximum height of 7 ft. 4 in. Turntables for vehicles, fuel and water tanks and other equipment located below decks limited the engine room to an overall length of 44 ft. Fig. 2 shows the profile of the vessel and the hull arrangement.

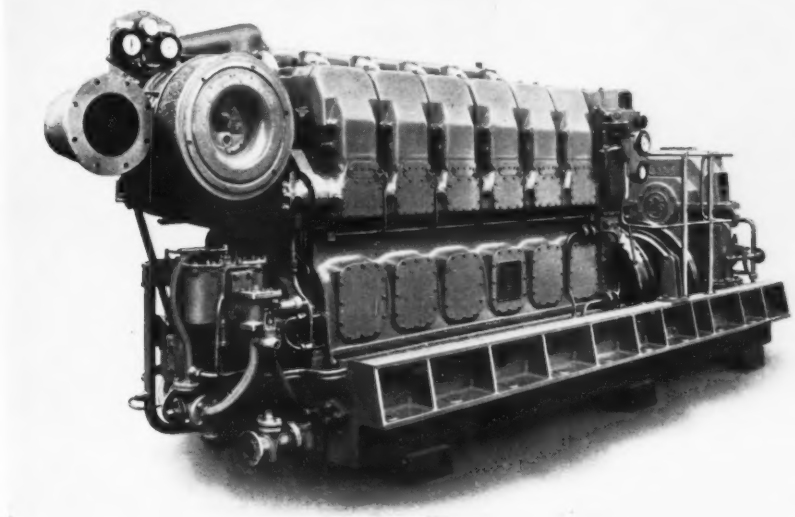


Fig. 3. The starboard '6SRKM' type turbo-pressure-charged diesel engine

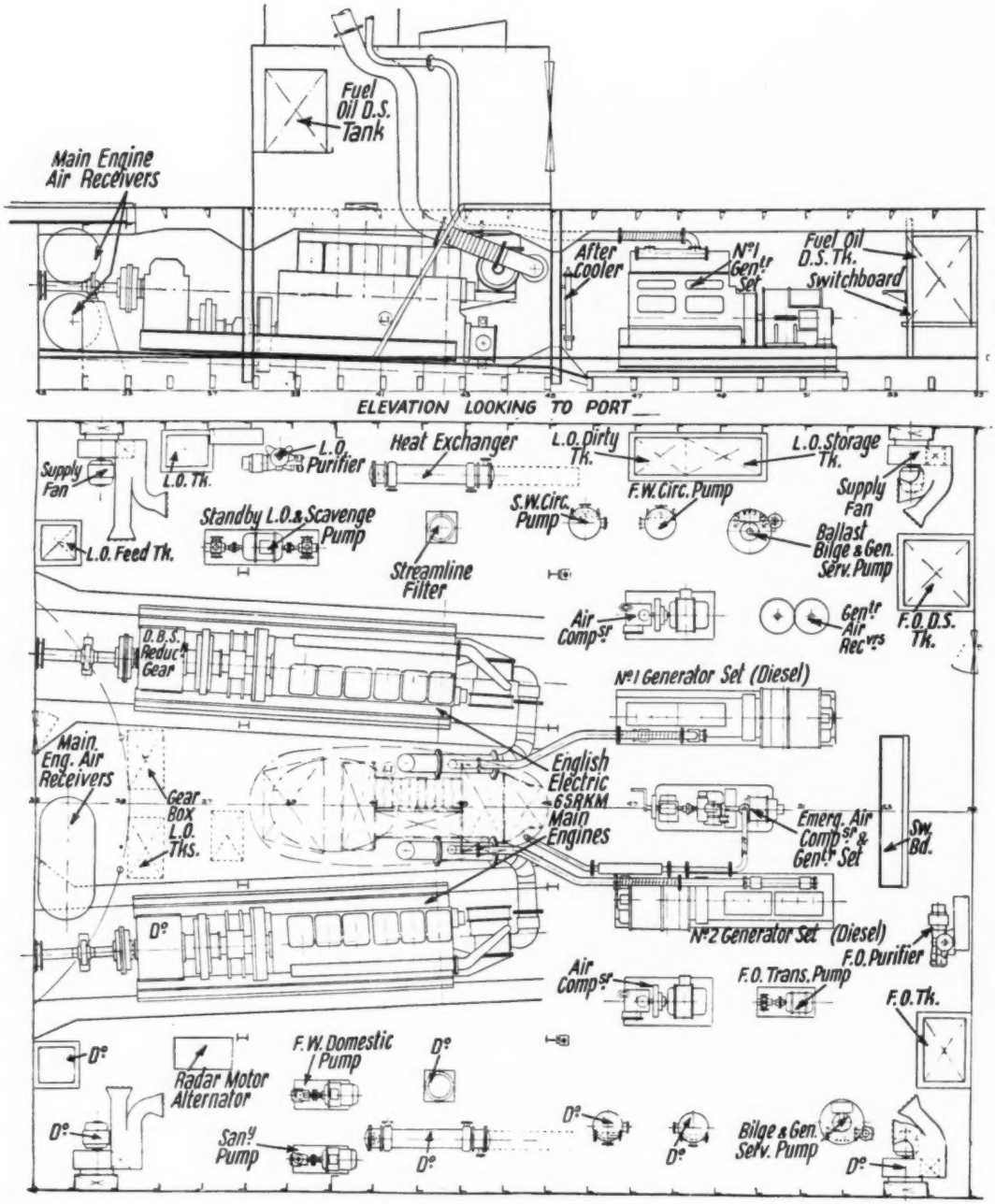


Fig. 4. Plan and elevation of machinery

When first considering the machinery it seemed that a twin screw diesel-electric installation most satisfactorily met the requirements of manœuvrability and availability, and it was therefore recommended by this Company. With a plant of this type, in a confined space, a number of small high-speed engines might appear to be the obvious choice, but this is not necessarily so. Allowance must be made for working space about each unit, and its various service connections ; the supply of ventilating air to the generators is a major problem and the switchgear must cater for the number of generators employed. As a result of these factors it is usually best to limit the number of engines to that necessary to meet the availability requirements. Experience has shown that two units are satisfactory in a diesel-electric vessel of this class ; in the event of failure in one set, the remaining 50% power will give the vessel 79% of full speed and, with the ' English Electric ' system of control, unimpaired manœuvrability. The service can thus usually be maintained, for the period necessary to complete repairs on a unit, without serious inconvenience.

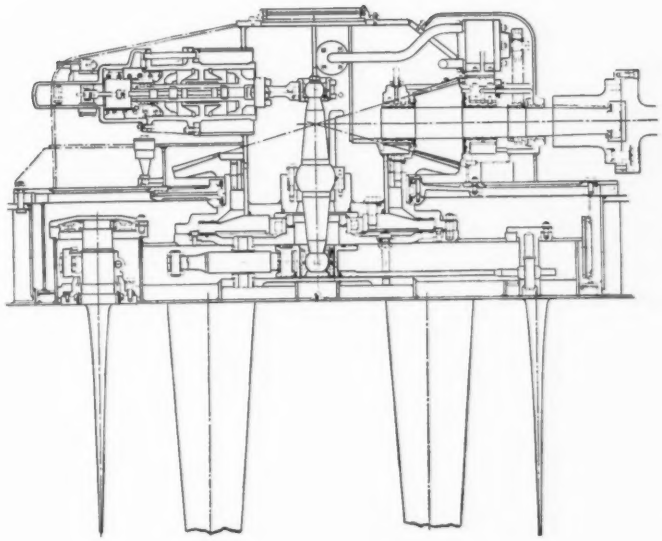


Fig. 5. Sectional arrangement of Voith-Schneider cycloidal propeller

This Company's medium-speed ' RKM ' diesel engines were developed for marine service and are excellent for such duty, but it seemed at first that the restricted headroom would preclude their use. By modifying the bedplate, and arranging that the pistons and connecting rods could be withdrawn separately, it was made possible to accommodate these engines. Extensive tank tests on a model of the vessel determined that 700 s.h.p. would be required at the propellers, and a twin screw diesel-electric installation was put forward with two generating sets, which could reasonably be installed within the machinery space available.

As the owners of the " Scotscraig " were not familiar with the capabilities of diesel-electric drive, manœuvring trials were carried out in the M.V. " Vecta " (with ' English Electric ' propulsion equipment) with the co-operation of the Isle of Wight Steam Packet Company, to test the response of this machinery. These trials confirmed that diesel-electric machinery on bridge control is greatly superior to orthodox machinery, when used with screw propellers. This is also true when the machinery is used to drive paddles. With the information obtained from " Vecta " as a basis, further tank tests were made on the model to determine the stopping power of screw propellers of the size which could be fitted within the limits of such shallow draft. It was found that cavitation reduced the braking effect of the screw propeller to the extent of introducing an element of risk, despite the rapidity of response of the diesel-electric drive. This risk arises from the necessity of approaching the terminals at relatively high speed, in adverse wind and tide conditions.

Since no comparable screw-propeller driven vessel was available for full-scale trials, the result of the model tests had to be accepted and an alternative considered. Paddles would have been satisfactory but as they could not be applied in the limiting dimensions, Voith-Schneider propellers were again considered. Experience with the " Abercraig " showed that they met manoeuvring and braking requirements, but being susceptible to damage in service the serious question of

availability remained. A characteristic of these propellers is that they can be unshipped without dry docking the vessel, and it was suggested that if two spare propellers were available, 'lay off' time would be reduced to that necessary to replace a damaged propeller for subsequent repair. These propellers are costly and the suggestion was not very sound, economically, when applied only to one ship.

It was decided, however, that if the spare propellers could be applied to the "Abercraig" also, the suggestion would be justified. To provide this arrangement the line of shafting in the new vessel had to be the same as that in the "Abercraig," and the shaft had to turn at 425 r.p.m. These propellers only require a uni-directional engine running at constant speed under governor control, and in consequence diesel-electric machinery is not necessary.

The problem was to line up the 'RKM' engines with the fixed shaft line, in the available headroom. To do this the crankshaft centre-line had to be 23 inches below the propeller shaft line, and the use of gearing permitted this with a ratio of 1.295 to 1 only. This ratio fixed the engine speed at 550 r.p.m. and, allowing for suitable de-rating in b.m.e.p., the required 370 b.h.p. per shaft was available from type '6SRKM' (6-cylinder pressure-charged) diesel engines.

The final proposal by The English Electric Company was for a pair of handed '6SRKM' engines, each coupled through a 'Bibby' detuner coupling to a 'David Brown' single-reduction double-helical gear, the engine and gearing being mounted on a fabricated combination baseplate. The unit is shown in Fig. 3. Although, owing to the rake of the propeller shafting, only 18 inches clearance exists between the top of No. 6 cylinder and the deck head, the piston and connecting rod can be removed, separately, without difficulty. Having established this important point, the proposal was accepted by the owners and builders.

Since it was not possible to provide a sump of sufficient capacity in the engine bedplate, semi-dry sump lubrication is employed. This arrangement consists of a separate tank and engine-driven

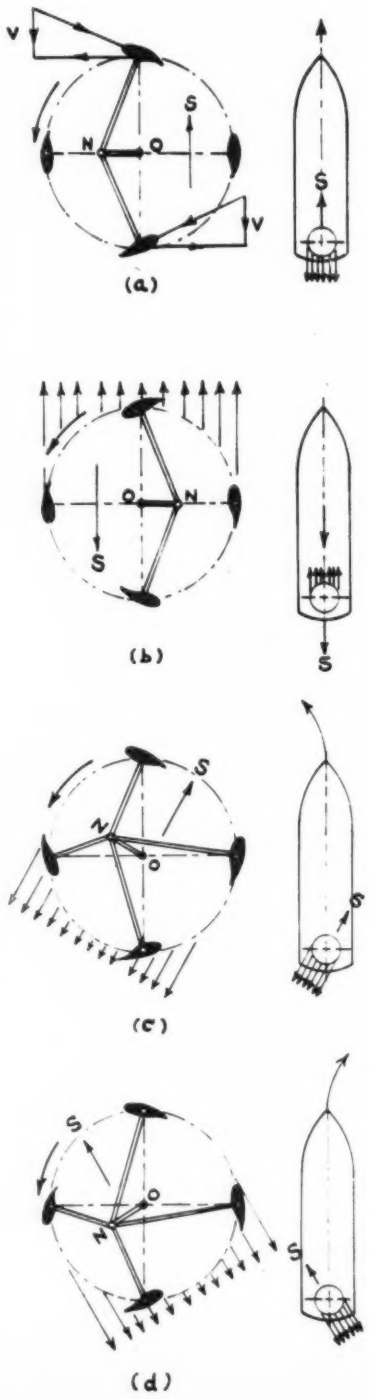


Fig. 6. (right) Principle and method of operation of the Voith-Schneider propeller

scavenge and pressure pumps. The gearing lubrication is on a separate system ; an integral pressure pump is driven from the primary shaft in the gear case and feeds the gearing bearings and sprayers.

Fresh water cooling is employed and each engine has its own heat exchanger ; the circulating water temperature is thermostatically controlled to meet automatically the frequent changes in engine load. The auxiliaries are electrically driven and power for these is supplied from two 75 kW, 220 volts D.C. diesel-driven generators.

The final machinery installation (Fig. 4) differs widely from the original project and has the disadvantages in comparison with it that availability may be affected by the vulnerability of the Voith-Schneider propellers, and the service cannot be maintained on one engine. As has been shown however, conditions dictated the adoption of this final arrangement, and it is gratifying that the vessel is operating to the entire satisfaction of her owners.

For those not familiar with the Voith-Schneider cycloidal propeller a brief description may be of interest. Leaving aside the question of its vulnerability, it has the following advantages :—

1. It is efficient in shallow draft vessels.
2. It is readily arranged for bridge control.
3. It permits a high order of manœuvrability.
4. Its prime mover is a constant speed, unidirectional unit.
5. It is able to steer as well as propel ; in consequence a rudder and its attendant mechanism is not necessary.
6. It can be unshipped for examination and repair, without dry docking the vessel.

The sectional arrangement in Fig. 5 shows the propeller as it is mounted in the vessel ; only the blades project beyond the hull plating. The drive from the intermediate shaft is through a bevel pinion and crown wheel, the latter being bolted to the fabricated runner assembly. Two oil-operated servo-motors disposed at 90 degrees to one another actuate a central ball-jointed control rod, the lower end of which terminates in a star centre. Radius arms connect the star centre to links on the blade shafts and determine the pitch angle of the blades relative to the orbit circle.

Running at constant r.p.m. the output of the propeller, and the direction of the resultant thrust, are governed by the movement of the star centre induced by the servo-motors. These servo-motors can be controlled from the bridge or other suitable location.

The principle and method of operation are shown in Fig. 6, from which it will be seen that the relative positions of the star centre ' N ' and the orbit centre ' O ' control the magnitude and direction of the thrust. When these centres coincide no thrust is developed ; movement of centre ' N ' in relation to ' O ' turns the blades in relation to the orbit circle, producing the thrust component ' V ' shown geometrically in Fig. 6 (*a*).

Centre ' N ' can operate in a circle about ' O ' permitting thrust in any direction ; thus it is possible to go astern without changing the direction of rotation of the propeller, and to manœuvre the vessel effectively in any direction with very little fore or aft motion. Where two of these propellers are installed it is possible to impart a purely ' thwartships ' motion to a vessel.

Main Line Diesel-Electric Locomotives for South Australia

TEN 1,760 H.P. MAIN line locomotives, powered by ' English Electric ' diesel-electric equipment, are being built by the South Australian Government Railways for service on the difficult south main line which crosses the Mount Lofty ranges in the first 45 miles after leaving Adelaide. This section of line carries a heavy freight traffic and is single tracked for most of its length. It also includes extremely severe gradients and sharp curvature ; in a distance of 14 miles, between Mitcham and Mount Lofty, the line rises 1,370 feet at an average grade of 1 in 54, concluding with 5 miles graded at 1 in 45 without compensation for practically continuous curvature of 10 chains radius.

The combination of severe gradients, curvature and single line working severely restricts the traffic capacity of this section, which is at present operated to its maximum capacity several times daily. The railway administration therefore wanted to increase the traffic capacity without incurring the very heavy cost of doubling the line through the Mount Lofty ranges. This could be achieved only by improved performance of trains ascending the steep gradients, thereby reducing line occupation times in the steeply graded sections and enabling the frequency of service to be increased. No appreciable improvement in up-grade performance could be obtained with the existing steam motive power, but diesel-electric locomotives develop a practically constant wheel tread horse-power over

Fig. 1. *Diesel-electric locomotive No.* 900, "*Lady Norrie*"

Fig. 2. Twin 1,760 h.p. diesel-electric locomotives Nos. 900 and 901 hauling the " Overland Limited Express " through the Mount Lofty ranges

a wide operating speed range and have a definite superiority, at low speeds, over steam locomotives of comparable rating.

The new locomotives are normally operated in pairs, forming a 3,520 h.p. unit, for hauling heavy freight trains between Mile End (Adelaide) and Tailem Bend, a distance of 74 miles which includes the severely graded section through the Mount Lofty ranges. A twin unit locomotive can haul a 600 ton freight train from Mile End to Mount Lofty (18¼ miles) in 46 minutes, compared with a normal time of 85 minutes with steam operation. The 4-8-4 type steam locomotives previously employed are powerful machines weighing 223 tons, with a maximum tractive effort of 53,000 lb, increased to 61,000 lb with steam booster in operation.

The diesel-electric locomotives also operate passenger services over this line, including the " Overland Limited Express " (Fig. 2) which links Adelaide with Melbourne and is operated by the South Australian Railways between Adelaide and Serviceton on the Victorian State border. The new rolling stock built for this service has increased the train weight from 500 to 600 tons but the use of the new motive power will enable the running time between Adelaide and Mount Lofty (19½ miles) to be reduced from 61 to 46 minutes, whilst the overall time from Adelaide to Tailem Bend will be reduced from 3 hours 50 minutes to 2 hours 39 minutes—a saving of 30%.

The first locomotive (Fig. 1) was completed in September 1951, and went into regular passenger service in the same month. This was the first diesel-electric main line locomotive to enter regular service on the Australian mainland, and it was named " Lady Norrie " after the wife of the Governor of South Australia. It is of interest to recall that The English Electric Company also supplied the diesel-electric equipment for Britain's

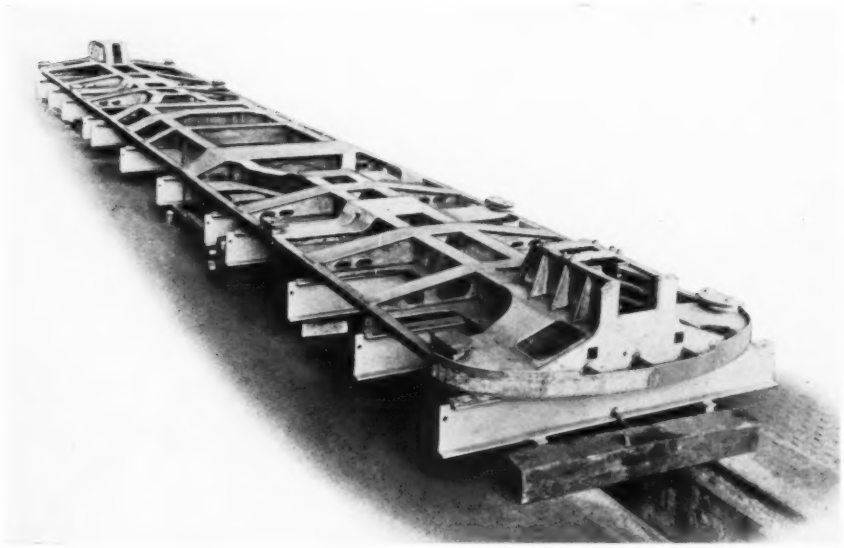


Fig. 3. Locomotive underframe (by courtesy of the South Australian Railways)

first main line diesel-electric locomotives Nos. 10,000 and 10,001.

Mechanical Parts

The mechanical parts for these locomotives were designed by the South Australian Railways, and are being built in the Railway's workshops at Islington.

The three-axle cast steel bogies which carry the weight of the locomotive superstructure are of the swing bolster type, each axle box being supported at the ends of compensating beams under the control of helical springs. Two nose-suspended traction motors are mounted in each bogie and drive the outer axles of the bogie through single reduction spur gearing. The cast steel frames of the bogies, supplied by Bradford Kendall Ltd., are the largest yet built in Australia.

The locomotive underframe (Fig. 3) is of the centre longitudinal type built up from rolled steel sections ; it is welded throughout. The cambered side-frame truss assists the underframe to take its loads. The nose and roof of the superstructure (Fig. 4) are of mild steel sheeting, and the sides are of metal-faced plywood.

Combined automatic and independent locomotive air braking is provided, operated from brake valves in the driving cab. Dynamic electric braking (described in some detail later) and hand brakes are also provided. Each locomotive is equipped with an air-cooled compressor with a capacity of 250 cu. ft/min. at 750 r.p.m. The compressor is driven from the diesel engine crankshaft through the auxiliary-drive case at the free end of the engine.

In the driving position (Fig. 5) are the master controller, the locomotive and train brake pedestals and the instrument panel including duplex pressure gauges for locomotive and train brakes, main and dynamic braking ammeters, fuel tank gauge and Hasler speed indicator and recorder. The figures and pointers of the instruments are treated with fluorescent paint and illuminated by ultra-violet light so that only the figures and pointers are visible after dark ; this feature is generally known as ' black lighting'.

The layout of the locomotives and the arrangement of the power and auxiliary equipment in the superstructure are shown in Fig. 6. An interior view of the engine room is given in Fig. 7.

Diesel Engine

The diesel engine, main generator and auxiliary generator form one unit (Fig. 8) which is supported

on resilient mountings to prevent racking stresses from the underframe being transmitted to the power unit. The sixteen cylinder, four stroke, Vee form, pressure charged diesel engine is rated, for this application, at 1,760 b.h.p. 750 r.p.m. at sea level. The cylinders have a bore of 10 in. and a stroke of 12 in., the piston speed at full load being 1,500 ft/min. The brake mean effective pressure is 123 lb/sq. in. and the maximum cylinder pressure 830 lb/sq. in. Fuel consumptions at 100%, 75% and 50% load are 0.392, 0.382 and 0.394 lb per b.h.p./hour respectively, based on fuel with a minimum calorific value of 19,350 B.Th.U. per lb. Similar engines operating at 850 r.p.m. are rated at 2,000 b.h.p.

The engine is provided with two mechanically driven water circulating pumps, one to each bank of cylinders, and with two lubricating oil pumps. These pumps are driven from the free end of the engine crankshaft. Of the two oil pumps, the scavenge pump draws oil from the engine sump and passes it through full-flow fabric filters to the oil radiator, from which oil passes to a storage tank. The pressure pump draws oil from this tank and passes it through a fine strainer to the main crankshaft bearings, from which it passes through drillings in the crankshaft to the connecting rod big end and gudgeon pin bearings. Forced lubrication is also provided to the camshaft bearings and to the camshaft and pump drives. The valve gear is lubricated at reduced pressure from the pressure oil pump of the engine lubricating system.

The oil and water elements of the radiator are arranged in four symmetrically disposed banks at the rear of the locomotive. The cooling fans, one of which is provided for each radiator bank, are driven by vertical-spindle motors which take their current supply from the main generator. These fans are thermostatically controlled and come into operation progressively with rising temperature. During dynamic braking two of these fans may be run at high speed with their motors connected across the traction motor armatures.

Fuel oil is carried in a tank of 1,000 gallons capacity mounted below the main frames and is fed to the engine through duplex filters by a motor-driven transfer pump. Two of these fuel transfer pumps are provided, a switch selecting the operation of one or the other. The motor driving the operating pump is connected to the battery when the master switch handle of the master controller is in any position except ' off.'

Air for engine combustion is drawn through viscous filters located in the locomotive body sides, and passes to a settling chamber formed by a removable roof section. Air trunking leads directly from the

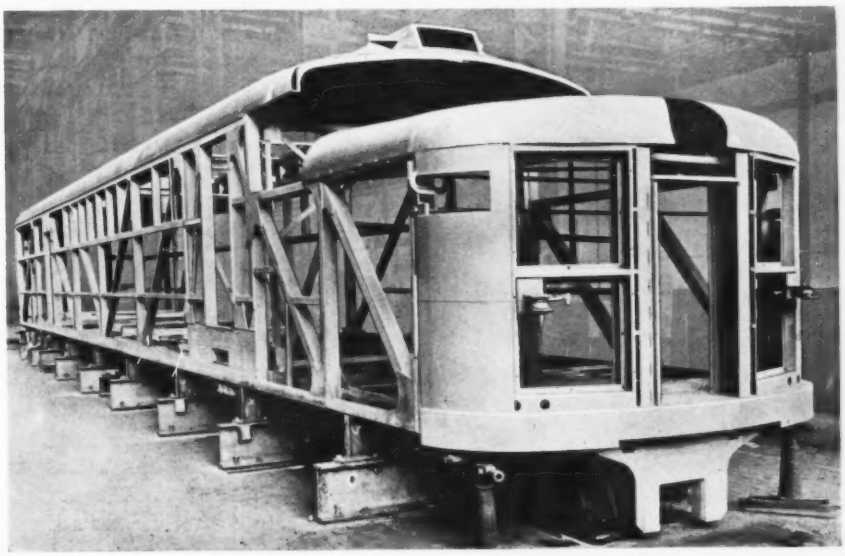


Fig. 4. *Locomotive superstructure during construction (by courtesy of the South Australian Railways)*

Fig. 5. Driving controls of 1,760 h.p. locomotive

settling chamber to the intakes of the engine turbo-chargers. Filtered air for engine-room cooling and pressurising is also taken from this settling chamber.

A servo-piston in the engine governor regulates the quantity of fuel delivered by the fuel injection pumps. The servo-piston is operated from the engine lubricating oil system. The governor is driven from one of the camshafts at the flywheel end of the engine.

The engine is started by motoring the main generator. For this purpose contactors connect a 240 ampere-hour, 48 cell, lead-acid type battery through a starting winding on the generator field to the armature. When the master controller handle is moved to the ' start ' position and the starting button in the engine room is depressed, the starting contactors and lubricating oil priming pump motor are energised simultaneously. When the priming pump has built up a predetermined lubricating oil pressure the fuel pump racks are opened to inject sufficient fuel for engine starting.

Electrical Equipment

The main generator, which is bolted and registered to a facing formed by an extension to the flywheel end of the engine bedplate, is a single-bearing self ventilated machine directly coupled to the engine crankshaft. It is continuously rated at 1,120 kW 700 volts 1,600 amperes. Separately excited and shunt field windings are provided; also the starting winding previously mentioned. The main generator draws cooling air from the pressurised engine compartment and expels heated air through ducting to an outlet in the roof of the superstructure.

The main generator supplies current to four nose-suspended axle-hung traction motors. The motors are series wound, each having a continuous full field rating of 310 h.p. 300 volts 875 amperes, and are connected in two parallel groups of two motors in permanent series. Two stages of traction motor field weakening are provided to ensure optimum locomotive performance throughout the road speed range. Cooling air for the motors is supplied by two blowers, one of which is mounted in the nose of the locomotive and the other at the rear of the superstructure. Each blower provides forced ventilation to a pair of motors.

The 35 kW auxiliary generator is a shunt wound machine overhung from the main generator. It supplies current for main generator field excitation, control circuit operation and battery charging. A regulating device is provided to maintain a constant output voltage from the auxiliary generator, irrespective of engine speed variation or changes in loading.

The dust-proof control cubicle houses the electro-pneumatic and electro-magnetic contactors, reverser and associated relays and fuses. The main and auxiliary control frames are shown in Figs. 9 and 10.

A torque regulator is provided automatically to adjust the field strength of the main generator during normal running, so that the output of the generator matches the available engine horse-power. This regulator is also used during dynamic braking to control the excitation of the main generator.

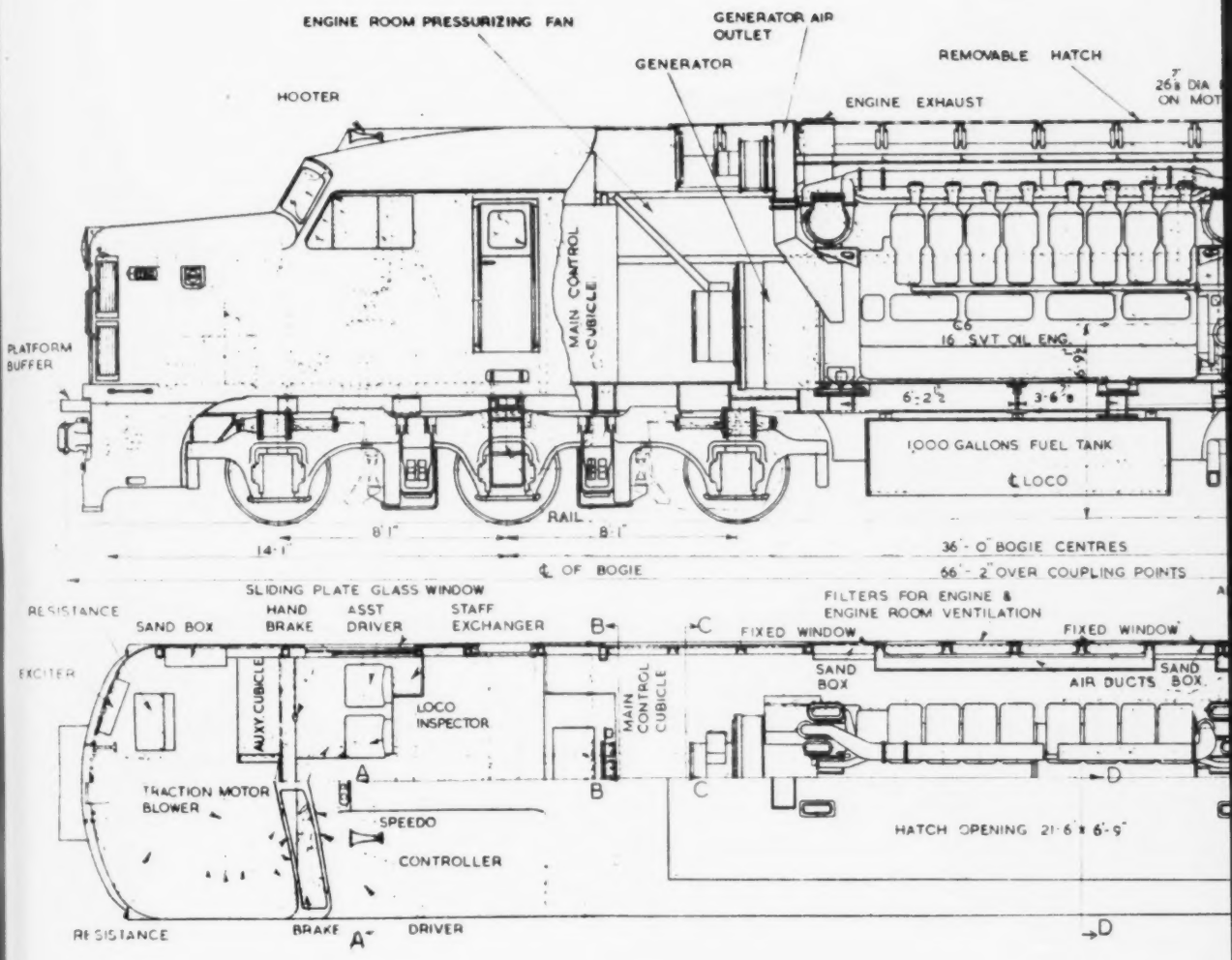
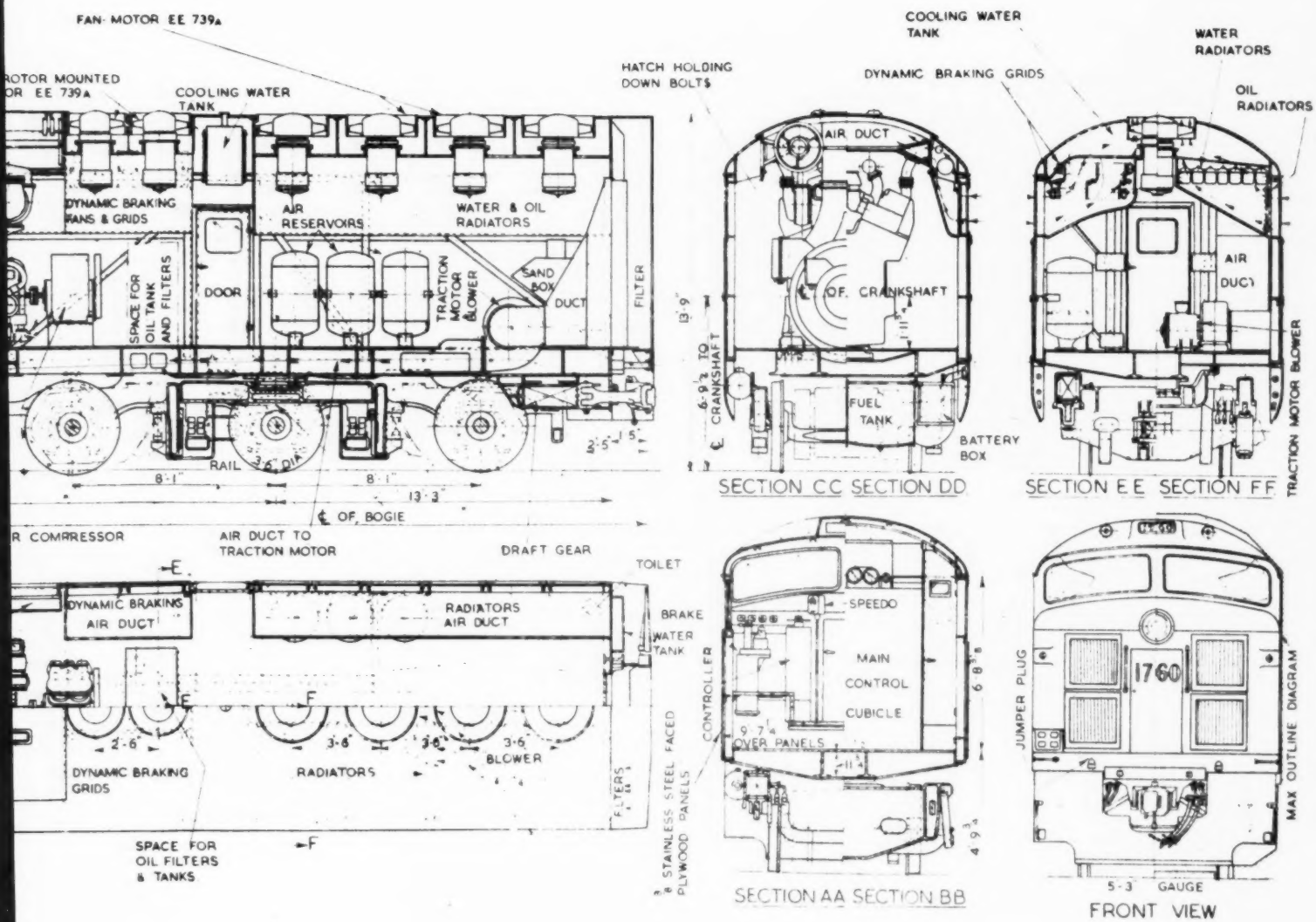


Fig. 6. General arrangement of locon



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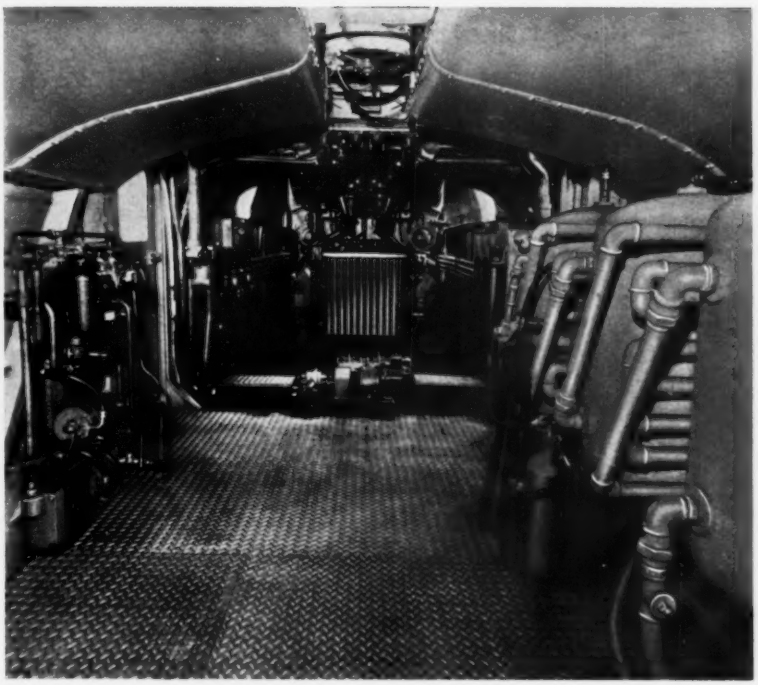

Fig. 7. Interior of engine room showing (right) main air reservoirs for braking system and (left) oil transfer pumps and filters. The air compressor is in the centre and the radiator fan motors are in the ceiling

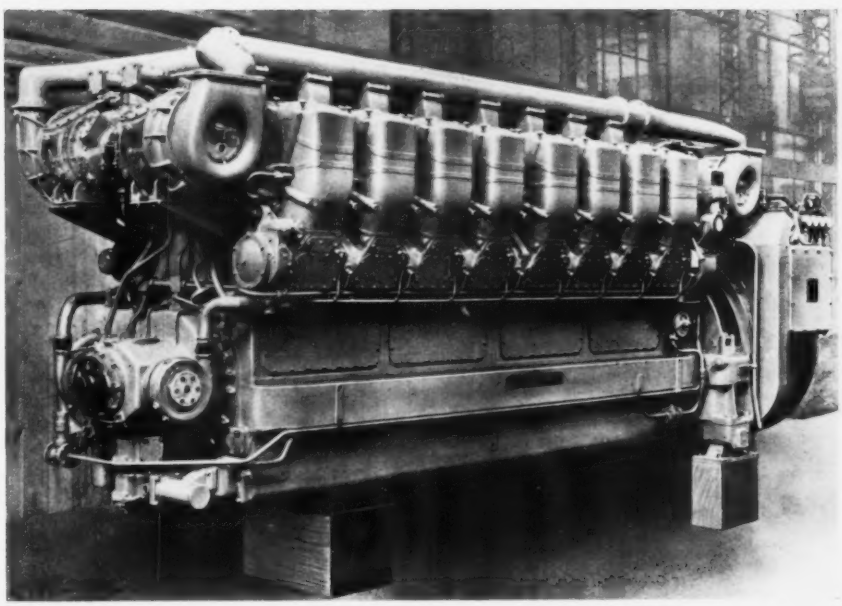

Fig. 8. 1,760 h.p. diesel engine with main and auxiliary generators

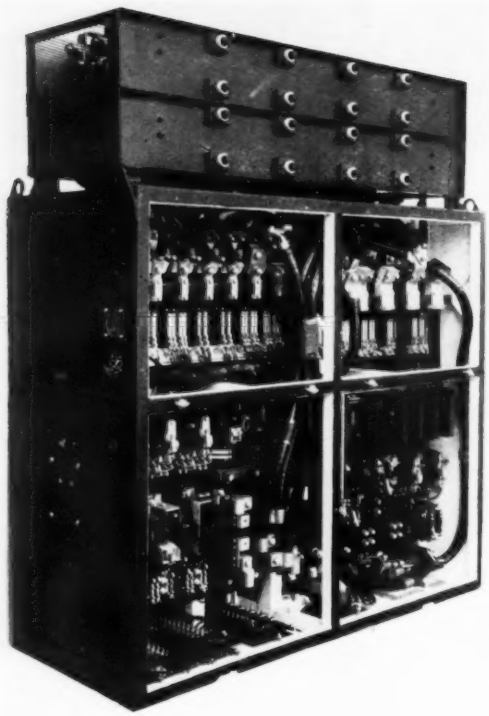

Fig. 9. Main control frame

The torque regulator (mounted on top of the auxiliary control frame) is connected in the main generator field circuit and is operated by a small motor. The control device on the diesel engine, which is operated by the servo-mechanism of the engine governor, causes the regulator motor to turn either in a clockwise or anti-clockwise direction when the diesel engine runs at speeds slightly higher or lower than normal. This variation in engine speed indicates under- or over-loading. The movement of the torque regulator gradually reduces the generator field strength when the engine is overloaded and its speed tends to fall, or increases the field strength when the engine loading is reduced and its speed tends to rise.

Dynamic Braking

The locomotives are equipped for dynamic braking which enables heavy trains to be held down to a moderate speed when descending steep gradients without continual application of the train brakes, with its consequent heavy rate of brake block wear. With dynamic braking a twin-unit locomotive can hold down the speed of a 600 ton train to 25 m.p.h. on a 1 in 45 falling gradient.

During dynamic braking the traction motors generate current which is absorbed by resistances, each pair of motors being connected to a separate resistance bank ; the motor fields are disconnected from their respective armatures and are connected in series to the main generator. Each resistance bank is cooled by a fan driven by a vertical-spindle motor connected across the bank.

The excitation of the traction motor fields during dynamic braking is obtained from the output of the main traction generator and is controlled through the excitation of the main generator field. The excitation of the main generator is controlled through the torque regulator, the operation of which has already been described for motoring conditions. Increase of excitation of the main generator field results in increased current through the traction motor fields, and consequently produces an increasing braking effort.

There are three positions of the master controller handle in connection with dynamic braking; when it is moved past the normal ' off ' position to its extreme travel, progressively increasing dynamic braking effort is obtained, in view of the fact that the torque regulator progressively increases the excitation of the main generator. When the master controller is notched back one notch from the position of extreme travel towards ' off ', a ' hold ' position is obtained wherein the torque regulator stops and therefore the braking effort remains substantially static. When the master controller handle is moved a further notch towards the ' off ' position it causes the torque regulator to reverse its direction of travel, thereby gradually decreasing the excitation of the main traction generator and thus decreasing the braking effort.

The dynamic braking feature may be cut out at any time by returning the master controller handle to the ' off ' position.

Indicating and Protective Devices

Lamps are provided in the driving-position instrument panel to indicate overload, wheel slip, the two stages of traction motor field weakening, and dynamic braking. In addition, safety devices are provided which may conveniently be summarised under three headings : (1) Warning devices consisting of indicator lights and an alarm buzzer. (2) Automatic protective devices which, in general, temporarily regulate the performance of the locomotive. (3) Automatic shut-down devices which stop the diesel engine or locomotive.

(1) *Warning Devices*

Indicator lights are fitted in the engine room to give warning of the following conditions, and during normal running they are all illuminated. On one of these conditions arising, the appropriate light is extinguished and the alarm buzzer sounds in the driving cab.

(*a*) Battery charging failure.
(*b*) High oil temperature.
(*c*) Blower motor failure.
(*d*) Low oil level.
(*e*) Low water level.
(*f*) High water temperature.
(*g*) Low oil pressure.

When operating in multiple unit, fault conditions are indicated by the lamps in the engine room of the locomotive concerned.

(2) *Automatic Protective Devices*

(*a*) High engine-water temperature switch. This runs the engine at idling speed until the water temperature has fallen to a safe value.

(*b*) Control-circuit governor. This ensures that the locomotive cannot be moved until the air pressure is sufficient to operate the train brakes correctly, and that the locomotive is made electrically inoperative should the air pressure in the train brake pipe fall to a low level.

(*c*) Automatic control switch. If the brake pipe pressure drops to the level at which an emergency brake application is made, dynamic braking is automatically cut out, thus preventing simultaneous use of air and dynamic braking on the locomotive.

(*d*) Overload devices, incorporated in the electrical circuits :—

(i) A torque control relay, which ensures that the load regulator is not operative until the main generator voltage is sufficiently high to preclude excessive current when the regulator commences to operate.

(ii) A current limit relay, which cuts out all stages of field diversion in any motor circuit in which the current value is too high.

(iii) Wheel slip relays, ensuring that when wheel slip occurs the power supply to the motors is automatically reduced until slipping ceases.

(iv) Overload relays, one connected in each motor circuit, which de-energise the motor contactors if the current in either circuit reaches a dangerously high value.

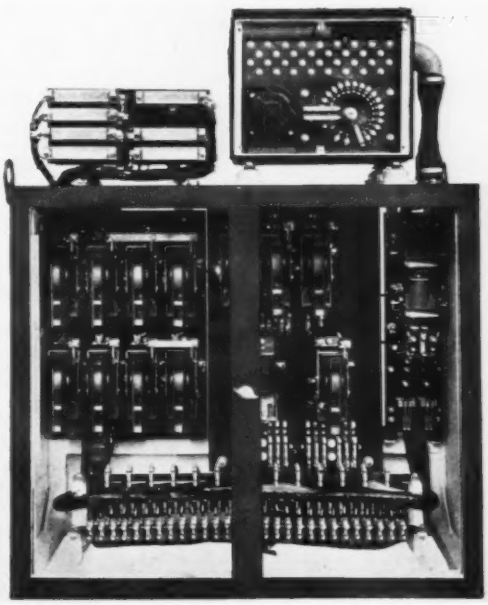

Fig. 10. *Auxiliary control frame*

(v) Dynamic brake control relay, which operates when the braking current exceeds a certain value and automatically prevents the driver from increasing the braking effort until the current has fallen below this value.

(3) *Automatic Shut-down Devices*

(*a*) Low water-level switch ; a float switch in the radiator header tank which stops the engine if the water level falls below a certain minimum.

(*b*) High oil-temperature switch, operated by a thermostat in the engine oil piping, which stops the engine when the oil reaches a dangerously high temperature.

(*c*) Low oil-pressure switch, which prevents the engine being started until an oil pressure of about 20 lb/sq. in. has been built up. When the engine is running, this switch stops the engine if the oil pressure falls below this value.

(*d*) Engine emergency governor, fitted to the engine camshaft, which at excessive engine speeds cuts off the fuel supply to the injectors thus stopping the engine.

(*e*) Locomotive overspeed device. The speedometer contains a contact which initiates an emergency brake application when the locomotive speed exceeds a predetermined maximum.

(*f*) ' Deadman's ' device, by means of which incapacitation of the driver causes power to be cut off and the train and locomotive brakes applied.

Operation

The master controller mounted in the cab of each locomotive incorporates a main control handle, reverser handle and master switch. The main control handle regulates the output of the engine-generator unit and also the dynamic braking effort. The ten power notches of the master controller correspond to progressively increased power outputs of the main generator, which are obtained by the use of engine speeds of 450, 620 and 750 r.p.m. in conjunction with varying degrees of generator field excitation. The master switch controls the starting and stopping of the diesel engine.

To start the diesel engine the master switch must first be moved to the ' start ' position, which provides a circuit to the engine starting button in the engine compartment. When this button is depressed the engine is rotated by motoring the generator in the manner already described.

When the engine fires, the master switch is moved to the ' engine only ' position in which the engine is run without excitation of the main generator fields. Before the locomotive can be moved, the reverser handle must be set to the direction of motion required and the master switch moved to the ' on ' position to energise the main generator field. The locomotive is then controlled by the main control handle, which is advanced step by step to the control notch required to obtain the desired power output. When the main control handle is advanced to the final power notch, the torque regulator previously described is brought into operation to adjust the excitation of the main generator, so that its output is matched with the available engine horse-power.